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SYSTEMATIC REVIEW

Effects of Wearing a Mask During Exercise on Physiological and Psychological Outcomes in Healthy Individuals: A Systematic Review and Meta-Analysis

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Abstract

Background Wearing face masks in public is an effective strategy for preventing the spread of viruses; however, it may negatively affect exercise responses. Therefore, this review aimed to explore the effects of wearing different types of face masks during exercise on various physiological and psychological outcomes in healthy individuals.

Methods A literature search was conducted using relevant electronic databases, including Medline, PubMed, Embase, SPORTDiscus, Web of Science, and Cochrane Central Register of Controlled Trials on April 05, 2022. Studies examining the effect of mask wearing (surgical mask, cloth mask, and FFP2/N95 respirator) during exercise on various physiological and psychological parameters in apparently healthy individuals were included. For meta-analysis, a random effects model was used. Mean difference (MD) or standardized MD (SMD) with 95% confidence intervals (CI) were calculated to analyze the total effect and the effect in subgroups classified based on face mask and exercise types. The quality of included studies was examined using the revised Cochrane risk-of-bias tool.

Results Forty-five studies with 1264 participants (708 men) were included in the systematic review. Face masks had significant effects on gas exchange when worn during exercise; this included differences in oxygen uptake (SMD − 0.66, 95% CI − 0.87 to − 0.45), end-tidal partial pressure of oxygen (MD − 3.79 mmHg, 95% CI − 5.46 to − 2.12), carbon dioxide production (SMD − 0.77, 95% CI − 1.15 to − 0.39), and end-tidal partial pressure of carbon dioxide (MD 2.93 mmHg, 95% CI 2.01–3.86). While oxygen saturation (MD − 0.48%, 95% CI − 0.71 to − 0.26) decreased slightly, heart rate was not affected. Mask wearing led to higher degrees of rating of perceived exertion, dyspnea, fatigue, and thermal sensation. Moreover, a small effect on exercise performance was observed in individuals wearing FFP2/N95 respirators (SMD − 0.42, 95% CI − 0.76 to − 0.08) and total effect (SMD − 0.23, 95% CI − 0.41 to − 0.04).

Conclusion Wearing face masks during exercise modestly affected both physiological and psychological parameters, including gas exchange, pulmonary function, and subjective discomfort in healthy individuals, although the overall effect on exercise performance appeared to be small. This review provides updated information on optimizing exercise recommendations for the public during the COVID-19 pandemic.

Systematic Review Registration Number This study was registered in the International Prospective Register of Systematic Review (PROSPERO) database (registration number: CRD42021287278).

Key Points

Wearing face masks during exercise affects gas exchange and pulmonary function.

A higher-level rating of perceived exertion, dyspnea, fatigue level, and thermal sensation was observed for mask wearing.

The overall effect of face masks on exercise performance appeared to be small in healthy individuals.

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1 Introduction

The outbreak of the novel coronavirus disease 2019 (COVID-19) was declared a pandemic by the World Health Organization (WHO) [1]. Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), which causes COVID-19, has infected 505 million people and caused more than 6 million deaths globally, as of April 2022 [1]. This virus is transmitted from person to person via airborne transmission, respiratory droplets, and aerosols, especially for those in close contact (e.g., distance < 1 m) with an infected person [2, 3]. Wearing face masks in public has proven to be an effective strategy to prevent the spread of the virus, thereby having a dual protective purpose in terms of protecting oneself as well as others from getting the viral infection [4, 5]. Therefore, wearing face masks in public is widely recommended by international and national authorities such as the Centers for Disease Control [6], the WHO [7], and the Government of Hong Kong [8].

Regular exercise is essential for healthy living and lowers the risk of cardiovascular diseases, diabetes mellitus, and obesity, which can increase the number and severity COVID-19-related symptoms [9]. However, during the COVID-19 pandemic, the closure of indoor fitness facilities and restrictions in terms of social distancing may lead to decreased exercise and physical activity levels [10]. The risk of viral transmission can be exacerbated during exercise because of heavy and rapid breathing [11], which necessitates wearing a face mask during exercise. Conversely, wearing a face mask during exercise may entail a physiological effect, such as a decrease in the maximal oxygen consumption (VO_{2max}) [12] and oxygen saturation (SpO_2) [13] and an increase in the partial pressure of end-tidal carbon dioxide ($PetCO_2$) [14], which may impair exercise performance or even create safety concerns. Moreover, studies have examined the effects of wearing a face mask on various physiological parameters using different exercise protocols, including a progressive exercise test using cycling [14], the 6-min walk test [13], and walking on a treadmill at a steady speed [15], with inconsistent results.

To our knowledge, only two systematic reviews have examined the effects of wearing face masks on physiological parameters during exercise. Shaw et al. reported that wearing face masks during exercise had no influence on exercise performance and only a minimal effect on physiological outcomes [16]. Another study identified a reduction in SpO_2 and a negative effect on the capacity for gas exchange and pulmonary function during exercise performed wearing N95/FFP2 or surgical masks [17]. The abovementioned systematic reviews conducted literature searches on March 23, 2021 [16], and May 05, 2021 [17], respectively. Since then, several studies related to this topic have been published, and a more updated systematic review focusing on the use of face masks during exercise in healthy individuals is necessary. Additionally, wearing a face mask during exercise can affect psychological indicators [18], which should also be considered when interpreting physiological findings. When wearing a mask during exercise, a higher-level rating of perceived exertion (RPE) and dyspnea was reported in one of the aforementioned systematic reviews [16]. Because of more recently published studies on this topic, more psychological indicators should be involved. Therefore, we conducted a systematic review and performed a meta-analysis to explore the effects of wearing a mask during exercise on both physiological and psychological parameters in healthy individuals.

2 Methods

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [19] recommendations were followed in this review protocol. The study was registered in the International Prospective Register of Systematic Reviews (PROSPERO) database (registration number: CRD42021287278).

2.1 Literature Search

Six electronic databases (Medline, PubMed, Embase, SPORTDiscus, Web of Science, and Cochrane Central Register of Controlled Trials) were searched for relevant studies on April 05, 2022. The search strategy is presented in Table S1 (see electronic supplementary material [ESM]). Two reviewers independently screened each article's title, abstract, and full text. Any discrepancies in the results were resolved by consulting a third independent reviewer.

2.2 Study Selection

Studies that met the following criteria were included in our systematic review: (i) studies including healthy individuals without any age limitations; (ii) studies including face masks, such as surgical masks, cloth masks, and FFP2/N95 respirators, which were available in the market and used by the general public while performing exercise; (iii) studies that performed comparisons among those wearing and not wearing ('no masks') face masks. (iv) the outcomes were physiological indicators (e.g., SpO_2, oxygen uptake [VO_2], carbon dioxide production [VCO_2], pulmonary function, heart rate, lactate), psychological responses (e.g., RPE,

thermal sensation, dyspnea, and fatigue level), and exercise performance; (v) the study adopted a randomized controlled design (crossover or parallel) or repeated measure design, (vi) studies were peer-reviewed and written in English. Studies were excluded if they (i) were comments, editorials, or reviews; (ii) involved participants with COVID-19 infection, or other clinical disease; (iii) included training masks.

2.3 Data Extraction

Two reviewers (CZ and KW) independently extracted the data. The characteristics of the included studies are summarized in Table 1. The following information was extracted: background (name of first author and year of publication), characteristics of participants (health status, number of participants, age, and sex), study design, exercise protocol, included mask types, physiological and psychological constituents studied, and main results.

For pooled analysis, the mean and standard deviation of physiological and psychological parameters in 'mask-on' and 'mask-off' conditions were extracted by two reviewers. The measurement at the end of the exercise period was retrieved, which reflected the most stressful point of the exercise test [16]. For example, if a progressive intensity protocol applied the exercise test until exhaustion, only the value at the end of the final phase was extracted. For missing data, the corresponding author of the study was contacted. If the missing data remained unavailable, the available graph data were extracted using WebPlotDigitizer [20].

2.4 Risk of Bias and Publication Bias

Two reviewers assessed the risk of bias for each included study using the revised Cochrane risk-of-bias tool for randomized trials (RoB 2) and RoB 2 additional considerations for crossover trials [21, 22]. This included six domains: randomization, period and carryover effects, deviation from the intended intervention, missing outcome data, measurement, and selection of reported results. Each domain was categorized as 'high risk,' 'some concerns,' or 'low risk,' and the six domains were used to rate the overall bias [22]. Moreover, funnel plots were constructed to visually represent the publication bias if at least 10 studies were included in the meta-analysis.

2.5 Statistical Analysis

The meta-analysis was performed using Review Manager version 5.4. software (The Cochrane Collaboration, 2020) and the random effects models (DerSimonian and Laird). Meta-analysis was used to perform a statistical analysis of the outcomes reported by at least four studies. Sub-group analyses were performed on different types of face masks if at least two studies examined the same type of face mask and on different types of exercise (progressive exercise test and steady-state exercise). Standardized mean differences (SMDs) with 95% confidence intervals (CIs) were determined to analyze exercise performance, VO_2, VCO_2, RPE, dyspnea, fatigue level, and thermal sensation, while the mean differences (MDs) and 95% CIs were used to analyze the remaining parameters. Sensitivity analyses were performed based on each study's risk-of-bias score and population. A p value < 0.05 was considered statistically significant. I^2 values were used to represent statistical heterogeneity and were classified as low (0–25%), moderate (26–50%), substantial (50–75%), and high (> 75%) [23].

3 Results

3.1 Study Selection

The review identified 8109 records on searching the six databases. After removing duplicates, 5696 articles remained, and 92 passed the title and abstract screening. Forty-seven articles were excluded for different reasons, including participants with clinical diseases or pregnancy ($n = 19$), no required face mask ($n = 9$), no suitable control group ($n = 9$), review or commentary paper ($n = 6$), and abstract only ($n = 4$). Finally, 45 and 43 articles were included in the present systematic review and meta-analysis, respectively, and the details of this process are shown in Fig. 1.

3.2 Characteristics of the Included Studies

Most included studies were randomized crossover studies ($n = 42$), while two studies were randomized controlled trials [24, 25] and one study used a non-randomized repeated measure [26]. Except for three studies that involved children [27–29], all the other studies involved adults, including athletes ($n = 3$) [30–32], recreational athletes ($n = 2$) [33, 34], and healthy adults ($n = 37$) [3, 12–15, 18, 24–26, 35–62], with a total of 1264 participants (708 men, 556 women) included. Overall, 37 studies included both men and women, while eight included only men. Surgical masks were used in 36 studies, in contrast to the 20 and eight studies that used the FFP2/N95 respirators and cloth masks, respectively.

Overall, 22 studies used a progressive exercise test [3, 12, 14, 18, 24, 26, 30, 35, 36, 39, 41, 43–45, 48, 50, 51, 53–55, 59, 60], while 19 employed the steady-state constant exercise test [13, 15, 25, 29, 31, 34, 37, 38, 40, 42, 46, 47, 49, 52, 56–58, 61, 62], and two used interval exercise tests [28, 32]. Moreover, one study used a resistance exercise test [33], and one used a sit-to-stand test [27].

Table 1 Description of included studies

Study	Participants' health status *N* (sex), age	Study design	Exercise protocol	Face mask	Outcomes	Main findings
Ade et al. (2021) [39]	Healthy $N = 11$ (5 males) 30 ± 11 years	Randomized crossover	PET (cycling): Increased at 20 W/min until the participant could not maintain the pedal cadence of 60 rpm Constant-load exercise: Cycling at 95 and 127 W	SM N95 Flannel mask NM	SpO_2 HR PO_2 PCO_2 RR Stroke volume Cardiac output Dyspnea	PET: SM/N95/Flannel mask vs NM: dyspnea ↑ Constant-load exercise: SM vs NM: HR ↑ (95 W) PO_2 ↓ PCO_2 ↑
Ahmadian et al. (2021) [24]	Healthy $N = 144$ (72 males) > 20 years	Randomized controlled	Submaximal exercise: Walking or jogging at a speed of 1.34 m/s with 5% grade for 20 min Maximal exercise (modified Bruce protocol): Stages 1–3 at 1.7 m/h and with 0, 5, and 10% gradients, stages 4–6 at 2.5, 4.2 and 5 m/h and with 12, 16 and 18% gradients	SM N95 NM	HR BP Hematological profiles	SM/N95 vs NM: NS
Akgül et al. (2021) [49]	Healthy $N = 30$ (16 males) 32 ± 1.07 years	Randomized crossover	1-h brisk walking (50–55% HR_{max})	SM NM	HR SpO_2 Pulse rate BP	SM vs NM: SpO_2 ↓
Alkan et al. (2021) [50]	Healthy $N = 26$ (11 males) 37.35 ± 15.99 years	Randomized crossover	PET (running) A maximal exercise test on a treadmill using the Bruce protocol	SM NM	Exercise duration VO_{2peak} VE RR HR BP MET SpO_2 Dyspnea Energy expenditure	SM vs NM: MET ↓ VO_{2peak} ↓ VE ↓ Energy expenditure ↓ Exercise duration (males) ↓ RR (males) ↓ HR (males) ↓
Bar-On et al. (2021) [52]	Healthy $N = 21$ (10 males) 29–57 years	Randomized crossover	Slow walk (4 km/h) at treadmill Brisk walk (7 km/h) at treadmill	SM NM	$EtCO_2$ SpO_2 RPE	SM vs NM: $EtCO_2$ ↑ RPE ↑
Boldrini et al. (2020) [38]	Healthy $N = 25$ (17 males) 34 ± 10 years	Randomized crossover	Repeated cycle ergometer tests (10 min at 100 W + 3 min at 150 W)	SM NM	HR Lactate RPE Dyspnea	SM vs NM: dyspnea ↑

Table 1 (continued)

Study	Participants' health status *N* (sex), age	Study design	Exercise protocol	Face mask	Outcomes	Main findings
Cabanillas-Barea et al. (2021) [25]	Healthy $N = 50$ (26 males) 20.96 ± 5.36 years	Randomized controlled	6-min walk test	SM FFP2/N95 NM	HR SpO_2 Distance Dyspnea	SM/FFP2/N95 vs NM: Dyspnea ↑
Dantas et al. (2021) [32]	Track and field athletes $N = 10$ (7 males) 23 ± 4 years	Randomized crossover	5×30 m sprints, with a passive 4-min interval between runs, performed on an outdoor running track	CM NM	Sprint times Accelerations RPE	CM vs NM: RPE ↑
Dirol et al. (2021) [13]	Healthy $N = 100$ (42 males) 40.87 ± 12.73 years	Randomized crossover	6-min walk test	SM NM	SpO_2 $EtCO_2$ RR HR BP Distance Discomfort Body temperature	SM vs NM: $EtCO_2$ ↑ HR ↑ RR ↑ SpO_2 ↓ Distance ↓
Doherty et al. (2021) [37]	Healthy $N = 12$ (7 males) 26 ± 3 years	Randomized crossover	8-min cycling trials on an electronically braked cycle ergometer (submaximal exercise intensity)	SM CM NM	HR RR SpO_2 Dyspnea $PetCO_2$ $PetO_2$ P_IO_2 P_ICO_2	Laboratory control and ecological control: CM vs SM, NM: Dyspnea ↑ Laboratory control: SM, CM vs NM: P_IO_2 ↑ Ecological control: CM vs NM: PetCO2 ↑ $PetO_2$ ↓
Driver et al. (2021) [12]	Healthy $N = 32$ (17 males) 23.2 ± 3.1 years	Randomized crossover	PET (running) Incremental cardiopulmonary exercise test using a Bruce treadmill protocol	CM NM	HR BP SpO_2 RPE Dyspnea VE VO_2 VE/VCO_2 RR VT Overall discomfort	CM vs NM: VO_2 ↓ VE ↓ SpO_2 ↓ RR ↓ VT ↓ HR ↑ Dyspnea ↑

Table 1 (continued)

Study	Participants' health status N (sex), age	Study design	Exercise protocol	Face mask	Outcomes	Main findings
Egger et al. (2021) [30]	Well trained, healthy athletes $N = 16$ (16 males) 27 ± 7 years	Randomized crossover	PET (cycling) Start at 100 or 150 W and workload was increased every 3 min by 50 W until exhaustion	FFP2 SM NM	Maximal performance HR BP VE VCO_2 VO_2 Lactate RPE	SM, FFP2 vs NM: maximal performance ↓ SM vs NM: lactate ↓ SM, FFP2 vs NM: VO_2↓ SM, FFP2 vs NM: VE↓
Epstein et al. (2021) [14]	Healthy $N = 16$ (16 males) 34 ± 4 years	Randomized crossover	PET (cycling) Start at 25 W and the load was increased every 3 min by 25 W until exhaustion	SM N95 NM	Time to exhaustion BP HR SpO_2 RR $EtCO_2$ RPE	N95 vs NM: $EtCO_2$ ↑ 100% exhaustion: SM vs NM: $EtCO_2$↑
Fikenzer et al. (2020) [3]	Healthy $N = 12$ (12 males) 38.1 ± 6.2 years	Randomized crossover	PET (cycling) Start at 50 W and the load was increased every 3 min by 50 W until exhaustion	FFP2/N95 SM NM	Maximal performance HR VO_{2max} VE PCO_2 PO_2 RR VT $avDO_2$ Lactate BP	FFPM vs NM: Maximal performance ↓ VO_{2max} ↓ $avDO_2$ ↓ VE ↓ RR ↓ VT ↓
Fukushi et al. (2021) [36]	Healthy $N = 24$ (15 males) 21.0 ± 0.8 y	Randomized crossover	PET (walking) Symptom limited graded exercise treadmill test using a modified Balke protocol	SM CM NM	Pulse rate SpO_2 RPE	SM, CM vs NM: Pulse rate ↑ RPE ↑
Goh et al. (2019) [29]	Healthy $N = 106$ (59 males) 7–14 years	Randomized crossover	Brisk walk on the treadmill (50–60% of predicted maximal HR)	N95 NM	$EtCO_2$ $FICO_2$ RR HR SpO_2	N95 vs NM: $EtCO_2$ ↑ $FICO_2$ ↑
Hoffmann (2021) [31]	Healthy, sports students $N = 38$ (16 males) 22.9 ± 2.6 years (males) 22.6 ± 1.3 years (females)	Randomized crossover	15-min endurance runs at a constant speed	SM CM NM	HR SpO_2 RPE	SM/CM vs NM: HR ↑ RPE ↑

Table 1 (continued)

Study	Participants' health status *N* (sex), age	Study design	Exercise protocol	Face mask	Outcomes	Main findings
Hua et al. (2021) [35]	Healthy $N=23$ (6 males) 26.9 ± 3.72 years	Randomized crossover	PET (running) Start at 8.0 km/h and increased by 2.0 km/h at 3-min intervals until the HR reached 190 beats/min	SM N95 NM	BP HR SpO_2 Vessel density Maximum running time Maximum running speed	SM/N95 vs NM: SpO_2 ↑ HR and vessel density in superficial plexus ↓ Maximum running time ↓ Maximum running speed ↓
Jesus et al. (2021) [62]	Healthy $N=32$ (16 males) 24.0 ± 3.3 years	Randomized crossover	Repeated cycle ergometer tests (10-min at ventilatory threshold work rate − 25% + 10-min at ventilatory threshold work rate + 25%)	SM NM	VO_2 VE VT VE/VCO_2 HR RR	Ventilatory threshold work rate + 25%: SM vs NM: VE ↓ VO_2 ↓ RR ↓ VE/VCO_2 ↓
Jones (1991) [61]	Healthy $N=10$ (10 males) 29.6 ± 4.4 years	Randomized crossover	PET (running) Incremental protocol with three 5-min stages at light (< 25% VO_{2max}), moderate (26–50% VO_{2max}), and heavy (51–75% VO_{2max}) intensity	N95 NM	HR RR BP	N95 vs NM: RR ↑ SBP (heavy intensity) ↑ DBP (moderate, heavy intensity) ↑ HR (heavy intensity) ↑
Kampert et al. (2021) [18]	Healthy $N=20$ (11 males) 25.0 ± 2.4 years (males) 25.1 ± 4.2 years (females)	Randomized crossover	PET (running) The grade increased beginning at the second min from 0.0 to 2.0% and increased in a fixed increment of 1.0% every min until volitional fatigue	N95 CM NM	VO_2 MET Ca-vO_2 SpO_2 HR RPE Overall discomfort	CM, N95 vs NM: VO_2 ↓ HR ↓ MET ↓ Ca-vO_2 ↓ CM, N95 vs NM: overall discomfort ↑
Kato et al. (2021) [40]	Healthy $N=12$ (8 males) 23 ± 3 years	Randomized crossover	Treadmill exercise for 30 min (6 km/h, 5% slope)	SM NM	HR Thermal sensation Thermal discomfort Humid sensation Physical fatigue Relative humidity of the face	SM vs NM: Thermal sensation ↑ Thermal discomfort ↑ Humid sensation ↑ Relative humidity of the face ↑
Kim et al. (2013) [15]	Healthy $N=20$ (13 males) 23 ± 2.9 years	Randomized crossover	1-h treadmill walk (5.6 km/h, 0% grade)	N95 with exhalation valves N95 without exhalation valves NM	tcPCO_2 SpO_2 HR RR	N95 vs NM: tcPCO_2 ↑ HR ↑ RR ↑

Table 1 (continued)

Study	Participants' health status N (sex), age	Study design	Exercise protocol	Face mask	Outcomes	Main findings
Kim et al. (2016) [56]	Healthy $N = 12$ (12 males) 23.5 ± 1.6 years	Randomized crossover	1-h treadmill exercise (5.6 km/h, 0% grade)	N95 P100 NM	SpO_2 $tcPCO_2$ HR RR RPE Breathing comfort Thermal sensation	N95/P100 vs NM: Breathing comfort ↑
Li et al. (2021) [41]	Healthy $N = 10$ (5 males) 21.00 ± 1.58 years (males) 21.20 ± 0.45 years (females)	Randomized crossover	PET (cycling) Start cycling at 0 W, 60 rpm for 2 min and the load was increased	SM NM	VO_2 SpO_2 HR VT Breathing reserve in percentage VE VE/VCO_2 RPE	SM vs NM: VT ↓ VE ↓ SM vs NM (females): VO_2 ↓ SM vs NM (males): HR ↓
Lässing et al. (2020) [42]	Healthy $N = 14$ (14 males) 25.7 ± 3.5 years	Randomized crossover	30-min cycling at maximal lactate steady state with a minimum frequency of 60 rpm	SM NM	$avDO_2$ BP HR RR VE VE/VCO_2 VCO_2 VO_2 VT RPE Inspiratory time Alveolar ventilation	SM vs NM: VCO_2 ↓ VO_2 ↓ VE ↓ RR ↓ $avDO_2$ ↓ SM vs NM: HR ↑ Inspiratory time ↑ Alveolar ventilation ↓
Mapelli et al. (2021) [43]	Healthy $N = 12$ (6 males) 40.8 ± 12.4 years	Randomized crossover	PET (cycling) Incremental cardiopulmonary exercise test using a personalized ramp protocol aimed at achieving peak exercise in 10 min	SM FFP2 NM	HR VCO_2 VO_2 VE RR VT $PetO_2$ $PetCO_2$ SpO_2 RPE	SM, FFP2 vs NM: VCO_2 ↓ VE ↓ VT ↓ SM vs NM: VO_2 ↓ SM, FFP2 vs NM: $PetCO_2$ ↑ FFP2 vs NM: $PetO_2$ ↓ SM vs NM: RR ↓ VO_2 ↓

Table 1 (continued)

Study	Participants' health status *N* (sex), age	Study design	Exercise protocol	Face mask	Outcomes	Main findings
Ng et al. (2022) [53]	Healthy, trained $N=8$ (4 males) 24.5 ± 3.3 years	Randomized crossover	PET (cycling) Began at 50 W and each 3 min the workload increased by 25 W until exhaustion	SM Taped filter mask NM	Maximal workload Time to exhaustion Dyspnea HR Lactate SpO_2	SM vs NM: Time to exhaustion ↓ Taped filter mask vs NM: Maximal workload ↓ Time to exhaustion ↓ Lactate ↓
Otsuka et al. (2020) [51]	Healthy $N=6$ (6 males) 24 ± 2.1 years	Randomized crossover	PET (cycling) The test proceeded to continuous pedaling exercises at a gradual load of 20 W per min	SM NM	Power output VO_2 VE RPE Anaerobic threshold time	SM vs NM: RPE ↑
Pimenta et al. (2021) [60]	Healthy health professionals $N=12$ (8 males) 29.8 ± 5.3 years	Randomized crossover	PET (running) A symptom-limited Bruce treadmill protocol	SM FFP2 NM	Exercise testing duration RPE Dyspnea SpO_2 HR	FFP2 vs NM: RPE ↑ Dyspnea ↑ SpO_2 ↓
Poon et al. (2021) [44]	Healthy $N=13$ (7 males) 21.9 ± 1.4 years	Randomized crossover	PET (running) Incremental protocol with three 6-min stages (light, moderate, and vigorous at 25, 50, and 75% maximal oxygen uptake, respectively)	SM NM	HR RPE Lactate SpO_2	Vigorous intensity: SM vs NM: RPE ↑
Reychler et al. (2022) [27]	Healthy, children $N=37$ (16 males); 8–11 years	Randomized crossover	1-min sit-to-stand tests	SM NM	HR SpO_2 RPE Tests performance	SM vs NM: RPE ↑
Roberge et al. (2010) [58]	Healthy $N=10$ (3 males) Mean 25 years	Randomized crossover	1-h treadmill walking at 1.7 and 2.5 m/h, respectively	N95 with exhalation valves N95 without exhalation valves NM	SpO_2 $PtcCO_2$ RR VT VE HR RPE Comfort scores	M95 vs NM: NS
Roberge et al. (2012) [57]	Healthy $N=20$ (13 males) 23 ± 2.8 years	Randomized crossover	Walked on a treadmill at a low-moderate work rate (5.6 km/h) for 1 h	SM NM	HR RR RPE SpO_2 $tcPCO_2$ Thermal sensation	SM vs NM: HR ↑ RR ↑ $tcPCO_2$ ↑

Table 1 (continued)

Study	Participants' health status N (sex), age	Study design	Exercise protocol	Face mask	Outcomes	Main findings
Rosa et al. (2021) [33]	Healthy recreational weightlifters $N=17$ (17 males) 27.5 ± 4.4 years	Randomized crossover	Bench press exercise: High intensity (70% of one maximum repetition) Moderate intensity (50% one maximum repetition)	FFP2/N95 NM	MPV HR RPE SpO_2 BP	FFP2/N95 vs NM: SpO_2 ↓ RPE ↑ MPV ↓ (high-intensity condition)
Rudi et al. (2021) [59]	Healthy $N=20$ (10 males) 33.4 ± 10.3 years	Randomized crossover	PET (cycling) An initial workload of 70 W for male and of 40 W for female participants followed by increases of 30 W every 3 min at 70–90 rpm	SM FFP2 NM	BP HR PO_2 PCO_2 RPE Peak performance	SM/FFP2 vs NM: PO_2 ↓ PCO_2 ↑ FFP2 vs NM: RPE ↑ Peak performance ↓
Shaw et al. (2020) [45]	Healthy $N=14$ (7 males) 28.2 ± 8.7 years	Randomized crossover	PET (cycling) Start ranged from 35 to 100 W and was increased 35 W every 2 min until volitional fatigue	SM CM NM	RPE HR SpO_2 Time to exhaustion Exercise performance	SM/CM vs NM: NS
Shaw et al. (2021) [28]	Youth hockey players $N=26$ (21 males) 11.7 ± 1.6 years	Randomized crossover	Simulated hockey period Six shifts, 20 s of 'easy' pedaling (40% peak power), 10 s of 'hard' pedaling (95% peak power), 20 s of 'easy' pedaling, with 5 min rests between shifts	SM NM	Peak power HR SpO_2 RPE Tissue oxygenation index	SM vs NM: Tissue oxygenation index ↓ (males: shifts 1–6; females: shifts 7) RPE ↑ (females, shifts 5–7)
Shui et al. (2022) [55]	Healthy $N=12$ (6 males) 34 ± 4 years	Randomized crossover	PET (cycling) The workload increased every 1 min by 15 W for female participants and 20 W for males at 55–65 rpm until exhaustion	SM N95 NM	Inspiratory flow Inspiratory time VT VE $PetCO_2$ RR HR VO_2 Dyspnea VE/VCO_2 VE/VO_2 VO_2/HR	SM/N95 vs NM: Inspiratory flow ↓ Inspiratory time ↑ VE ↓ VO_2 ↓ RR ↓ VO_2/HR ↓ Dyspnea ↑ VT ↓ (only SM) VE/VO_2 ↓ (only N95) VE/VCO_2 ↓ (only N95) $PetCO_2$ ↓ (only N95)

Table 1 (continued)

Study	Participants' health status *N* (sex), age	Study design	Exercise protocol	Face mask	Outcomes	Main findings
Steinhilber et al. (2022) [54]	Healthy $N=39$ (20 males) 38.2 ± 14.2 years	Randomized crossover	Physical working capacity (PWC) submax test: Cycling started with 25 W or 50 W and increased every 2 min by 25 W until the level corresponding to 70–80% of the initial PWC_{max} was reached	SM FFP2 CM NM	SpO_2 SBP DBP RR $tcPCO_2$ Perceived respiratory effort Perceived physical exertion	SM/FFP2/CM vs NM: Perceived respiratory effort ↑
Tornero-Aguilera et al. (2021) [34]	Healthy recreational athletes $N=72$ (45 males) 28.1 ± 5.8 years	Randomized crossover	50- and 400-m maximal running tests (outdoor testing)	SM NM	Lactate RPE SpO_2 HR Subjective perceived stress Glucose	SM vs NM: Time ↑ Lactate ↑ Glucose ↑ RPE ↑ Subjective perceived stress ↑ SM vs NM: SpO_2 ↓
Umutlu et al. (2021) [26]	Healthy sedentary $N=14$ (7 males) 40 y (males) 34 years (females)	Repeated measures	PET (walking) Start at 4.5 km/h and speed was increased 0.5 km/h upon completion of each 10 min intervals throughout 4 stages	SM NM	VO_2 VCO_2 Energy expenditure HR BP VE RR	SM vs NM: VO_2 ↓ VCO_2 ↓ Energy expenditure ↓
Wong et al. (2020) [46]	Healthy with various sport backgrounds $N=23$ (10 males) 35.1 ± 12.7 years (males) 32.7 ± 9.9 years (females)	Randomized crossover	6-min treadmill walking (4 km/h, 10% grade)	SM NM	HR RPE	SM vs NM: HR ↑ RPE ↑
Yoshihara et al. (2021) [47]	Physically active $N=12$ (8 males) 24 ± 3 years	Randomized crossover	60 min of walking and jogging between 35 and 60% of relative VO_{2max}	SM N95 Sport mask Gaiter mask NM	HR RPE Thermal sensation Thirst level Fatigue level Breathing discomfort	Mask-on group vs NM: Breathing discomfort ↑

Table 1 (continued)

Study	Participants' health status *N* (sex), age	Study design	Exercise protocol	Face mask	Outcomes	Main findings
Zhang et al. (2021) [48]	Healthy $N = 71$ (35 males) 27.77 ± 7.76 years	Randomized crossover	PET (cycling) Start at 0 W, and the participants pedaled the cycle according to the set incremental power (15–25 W/min) at 60 rpm until exhaustion	SM NM	RPE Dyspnea VCO_2 VO_2 VE VE/VO_2 VE/VCO_2 $PetO_2$ $PetCO_2$ MET RER RR VT SpO_2 BP HR Breathing reserve	SM vs NM: VCO_2, ↓ VO_2 ↓ MET ↓ VT (peak) ↓ VE (peak) ↓ $PetO_2$ ↓ VE/VO_2 ↓ VE/VCO_2 ↓ HR (peak) ↓ RR ↑ $PetCO_2$ ↑ Dyspnea ↑

$avDO_2$ arterial-venous oxygen difference, *BP* blood pressure, *BR* breathing reserve, *$Ca\text{-}vO_2$* the calculation of estimated arterio-venous oxygen content difference, *CM* cloth mask, *DBP* diastolic blood pressure, *$EtCO_2$* end-tidal carbon dioxide, *$FetCO_2$* end-tidal fractional carbon dioxide concentration, *FFP* filtering facepiece, *$FICO_2$* fractional concentration of inspired CO_2, *HR* heart rate, *HR_{max}* heart rate maximal, *HRR* heart rate reserve, *MAP* mean arterial pressure, *MET* metabolic equivalent, *MPV* mean propulsive velocity, *NS* no significant difference, *N95* N95 respirator, *NM* no mask, *PCO_2* partial pressure of carbon dioxide, *PET* progressive exercise test, *$PetCO_2$* end-tidal carbon dioxide partial pressure, *$PetO_2$* end-tidal oxygen partial pressure, *P_ICO_2* partial pressure of inspired carbon dioxide, *P_IO_2* the partial pressure of inspired oxygen, *PO_2* partial pressure of oxygen, *$PtcCO_2$* transcutaneously measured partial pressure of carbon dioxide, *RER* respiratory exchange ratio, *RPE* rating of perceived exertion, *RR* respiratory rate, *SBP* systolic blood pressure, *SM* surgical mask, *SpO_2* arterial oxygen saturation, *$tcPCO_2$* transcutaneous carbon dioxide, *VCO_2* carbon dioxide production, *VE* minute ventilation, *VE/VCO_2* carbon dioxide ventilation equivalent, *VE/VO_2* ventilatory equivalents for oxygen, *VO_2* oxygen production, *VO_{2max}* maximal oxygen consumption, *VO_{2peak}* peak oxygen consumption, *VO_2/HR* oxygen pulse, *VT* tidal volume

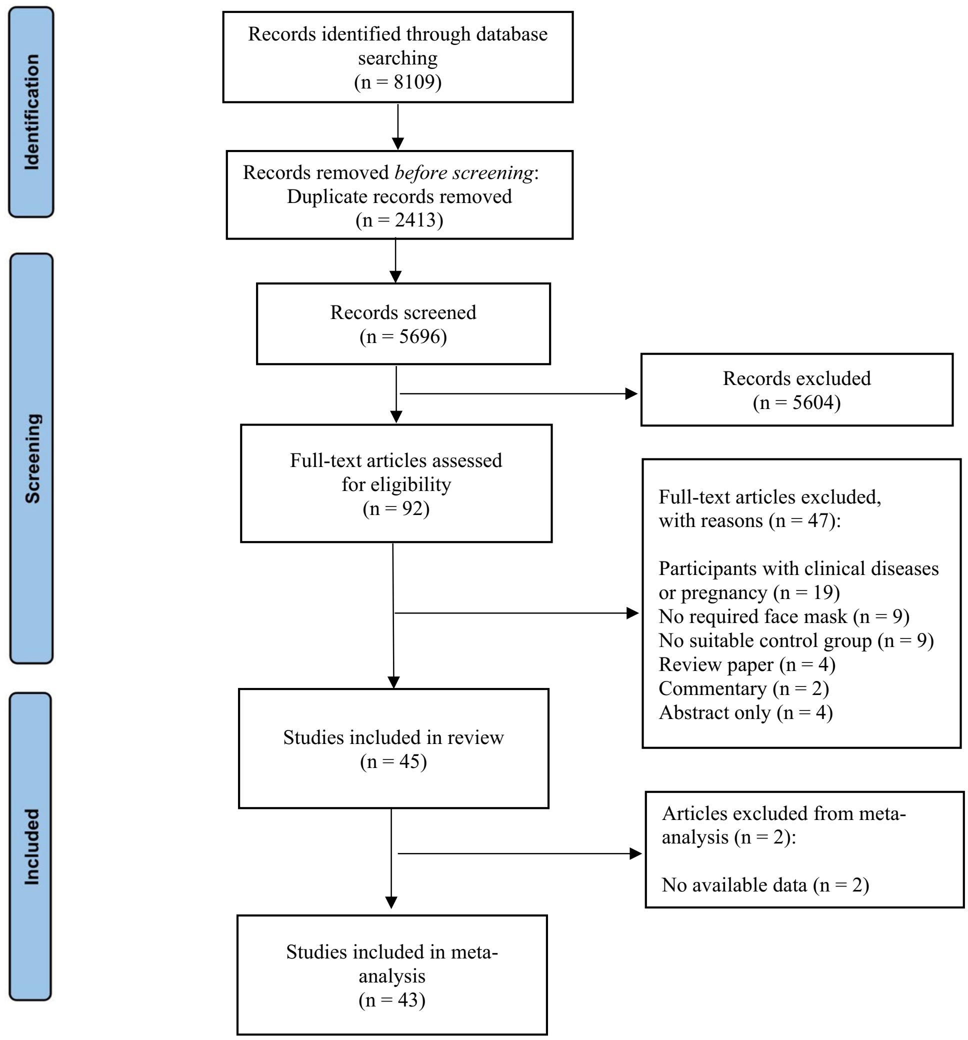


Fig. 1 Flowchart of publications included in systematic review and meta-analysis (PRISMA diagram). *PRISMA* Preferred Reporting Items for Systematic Reviews and Meta-Analyses

3.3 Physiological Outcomes

3.3.1 Heart Rate

The most common parameter analyzed was heart rate, which was reported in 40 articles [3, 12–15, 18, 24–31, 33–35, 37–50, 53, 55–62]. A total of 37 studies were included in the meta-analysis, including data extracted using WebPlotDigitizer from three studies [37, 61, 62]. Three studies were excluded because raw data were unavailable [24, 26, 27]. In the meta-analysis, in a comparison with 'no masks,' no significant differences were observed in those wearing surgical masks (MD 0.96 bpm, 95% CI − 1.01 to 2.93; $p = 0.34$, $I^2 = 63\%$), FFP2/N95 respirators (MD 1.63 bpm, 95% CI − 2.79 to 6.05; $p = 0.47$, $I^2 = 85\%$), cloth masks (MD − 0.94 bpm, 95% CI − 6.39 to 4.52; $p = 0.74$, $I^2 = 62\%$), and the total effect (MD 1.08 bpm, 95% CI − 0.69 to 2.85; $p = 0.23$, $I^2 = 77\%$), as shown in Fig. 2. When only steady-state exercise was included, a significant increase was noted in heart rate ($p < 0.01$), as shown in Table 2. When the studies with a high risk of bias or studies that involved children were removed, there was still no effect on heart rate.

3.3.2 Oxygen Uptake, End-Tidal Partial Pressure, and Saturation

A total of 12 studies reported the effect of wearing a face mask on VO_2 [3, 12, 18, 26, 30, 42, 43, 48, 50, 51, 55, 62]. The results of our meta-analysis revealed a significant decrease in VO_2 (SMD − 0.66, 95% CI − 0.87 to − 0.45; $p < 0.01$, $I^2 = 43\%$) when performing exercise while wearing face masks, as shown in Fig. 3a. In the sub-group analysis, a significant decrease was noted in VO_2 in those with surgical masks ($p < 0.01$) and FFP2/N95 respirators ($p = 0.01$), whereas no change was noted in those with cloth masks ($p = 0.25$). When considering the exercise type, a significant reduction was noted in the VO_2 in both progressive (SMD − 0.68, 95% CI − 0.93 to − 0.43; $p < 0.01$, $I^2 = 48\%$) and steady-state (SMD − 0.57, 95% CI − 0.94 to − 0.21; $p < 0.01$, $I^2 = 21\%$) exercise (Table 2). Six studies reported

Study or Subgroup	Face mask Mean [bpm]	Face mask SD [bpm]	Face mask Total	No face mask Mean [bpm]	No face mask SD [bpm]	No face mask Total	Weight	Mean Difference IV, Random, 95% CI
1.2.1 Surgical mask								
Zhang et al. 2021 [48]	165.8	15.7	71	171	13.7	71	2.5%	-5.20 [-10.05, -0.35]
Yoshihara et al. 2021 [47]	169.17	12.77	12	165.58	11.38	12	1.6%	3.59 [-6.09, 13.27]
Wong et al. 2020 [46]	128.4	13.2	23	124.4	12.8	23	2.0%	4.00 [-3.51, 11.51]
Tornero-Aguilera et al. 2021 (50m) [34]	110.6	35.1	72	106.3	35.3	72	1.3%	4.30 [-7.20, 15.80]
Tornero-Aguilera et al. 2021 (400m) [34]	167.6	25.92	72	152.4	15.9	72	2.1%	15.20 [8.18, 22.22]
Shui et al. 2022 [55]	168	16	12	176	12	12	1.4%	-8.00 [-19.32, 3.32]
Shaw et al. 2021 [28]	148.05	23.81	26	148.79	21.77	26	1.2%	-0.74 [-13.14, 11.66]
Shaw et al. 2020 [45]	179	19	14	179	16	14	1.2%	0.00 [-13.01, 13.01]
Rudi et al. 2021 [59]	177.8	10.3	20	180.9	11.1	20	2.1%	-3.10 [-9.74, 3.54]
Roberge et al. 2012 [57]	128.3	15.6	20	116.9	15.6	20	1.6%	11.40 [1.73, 21.07]
Poon et al. 2021 [44]	171.6	9.2	13	171.8	9.4	13	2.0%	-0.20 [-7.35, 6.95]
Pimenta et al. 2021 [60]	173	14.6	12	170.1	14.4	12	1.3%	2.90 [-8.70, 14.50]
Ng et al. 2022 [53]	185	3	8	189	5	8	2.6%	-4.00 [-8.04, 0.04]
Mapelli et al. 2021 [43]	168	16	12	170	14	12	1.3%	-2.00 [-14.03, 10.03]
Lässing et al. 2020 [42]	160.1	11.2	14	154.5	11.4	14	1.8%	5.60 [-2.77, 13.97]
Li et al. 2021 (Males) [41]	170.6	11.33	5	177.6	10.5	5	1.1%	-7.00 [-20.54, 6.54]
Li et al. 2021 (Females) [41]	162.6	21.72	5	162.6	17.67	5	0.4%	0.00 [-24.54, 24.54]
Kato et al. 2021 [40]	171	14	12	169	15	12	1.3%	2.00 [-9.61, 13.61]
Jesus et al. 2021 (WRVT - 25%) [62]	148.56	13.62	32	147.35	13.01	32	2.2%	1.21 [-5.32, 7.74]
Jesus et al. 2021 (WRVT + 25%) [62]	186.69	10.59	32	185.48	9.38	32	2.5%	1.21 [-3.69, 6.11]
Hua et al. 2021 [35]	173.3	10.07	23	157.2	7.24	23	2.5%	16.10 [11.03, 21.17]
Hoffmann et al. 2021 [31]	155.5	17.1	14	151.4	17.7	38	1.5%	4.10 [-6.48, 14.68]
Fikenzer et al. 2020 [3]	183	9.2	12	187	8.3	12	2.1%	-4.00 [-11.01, 3.01]
Epstein et al. 2021 [14]	165.81	16.01	16	170.5	11.71	16	1.6%	-4.69 [-14.41, 5.03]
Egger et al. 2021 [30]	189	9	16	191	9	16	2.2%	-2.00 [-8.24, 4.24]
Doherty et al. 2021 [37]	143.15	8.81	12	139.78	11.4	12	1.9%	3.37 [-4.78, 11.52]
Dirol et al. 2021 [13]	94.06	17.03	100	91.47	18.27	100	2.5%	2.59 [-2.31, 7.49]
Cabanillas-Barea et al. 2021 [25]	99.86	25.74	50	107.24	33.53	50	1.3%	-7.38 [-19.10, 4.34]
Boldrini et al. 2020 [38]	150	19	25	150	21	25	1.4%	0.00 [-11.10, 11.10]
Alkan et al. 2021 (45-64y) [50]	153.76	17.41	13	157.92	13.57	13	1.3%	-4.16 [-16.16, 7.84]
Alkan et al. 2021 (18-25y) [50]	179.38	11.66	13	185.54	8.84	13	1.9%	-6.16 [-14.11, 1.79]
Akgul et al. 2021 [49]	111.8	1.18	30	111.6	1.35	30	3.1%	0.20 [-0.44, 0.84]
Ade et al. 2021 [39]	138	27	5	135	26	5	0.3%	3.00 [-29.85, 35.85]
Subtotal (95% CI)			**816**			**840**	**57.0%**	**0.96 [-1.01, 2.93]**
Heterogeneity: Tau² = 14.58; Chi² = 86.88, df = 32 (P < 0.00001); I² = 63%								
Test for overall effect: Z = 0.96 (P = 0.34)								
1.2.2 FFP2/N95								
Yoshihara et al. 2021 [47]	166.25	16.51	12	165.58	11.38	12	1.4%	0.67 [-10.68, 12.02]
Shui et al. 2022 [55]	172	13	12	176	12	12	1.6%	-4.00 [-14.01, 6.01]
Rudi et al. 2021 [59]	177.4	12.4	20	180.9	11.1	20	2.0%	-3.50 [-10.79, 3.79]
Rosa et al. 2021 (Moderate intensity) [33]	135.3	21	17	138.3	22.9	17	1.0%	-3.00 [-17.77, 11.77]
Rosa et al. 2021 (High intensity) [33]	140.8	15.5	17	140.8	18.9	17	1.3%	0.00 [-11.62, 11.62]
Roberge et al. 2010 (2.5 m/h) [58]	101.3	9.4	10	101.3	11.8	10	1.7%	0.00 [-9.35, 9.35]
Roberge et al. 2010 (1.7 m/h) [58]	94.8	10.3	10	92.3	8.2	10	1.9%	2.50 [-5.66, 10.66]
Pimenta et al. 2021 [60]	170.8	13.8	12	170.1	14.4	12	1.4%	0.70 [-10.58, 11.98]
Mapelli et al. 2021 [43]	167	16.1	12	170	14	12	1.3%	-3.00 [-15.07, 9.07]
Kim et al. 2016 [56]	105.9	11.9	12	106.2	14.8	12	1.4%	-0.30 [-11.04, 10.44]
Kim et al. 2013 [15]	124.3	15.8	20	114.9	12.1	20	1.8%	9.40 [0.68, 18.12]
Kampert et al. 2021 [18]	174	9	20	177	10	20	2.3%	-3.00 [-8.90, 2.90]
Jones. 1991 [61]	150	15	10	137	18	10	1.0%	13.00 [-1.52, 27.52]
Hua et al. 2021 [35]	181.4	6.89	23	157.2	7.24	23	2.6%	24.20 [20.12, 28.28]
Goh et al. 2019 [29]	110.2	7.73	106	108.4	9.84	106	2.9%	1.80 [-0.58, 4.18]
Fikenzer et al. 2020 [3]	182	11.2	12	187	8.3	12	1.9%	-5.00 [-12.89, 2.89]
Epstein et al. 2021 [14]	168.81	12.84	16	170.5	11.71	16	1.8%	-1.69 [-10.20, 6.82]
Egger et al. 2021 [30]	191	7	16	191	9	16	2.4%	0.00 [-5.59, 5.59]
Cabanillas-Barea et al. 2021 [25]	105.67	32.2	50	107.24	33.53	50	1.2%	-1.57 [-14.46, 11.32]
Ade et al. 2021 [39]	137	25	11	135	26	11	0.6%	2.00 [-19.32, 23.32]
Subtotal (95% CI)			**418**			**418**	**33.3%**	**1.63 [-2.79, 6.05]**
Heterogeneity: Tau² = 76.08; Chi² = 126.09, df = 19 (P < 0.00001); I² = 85%								
Test for overall effect: Z = 0.72 (P = 0.47)								
1.2.3 Cloth mask								
Shaw et al. 2020 [45]	182	12	14	179	16	14	1.5%	3.00 [-7.48, 13.48]
Kampert et al. 2021 [18]	174	10	20	177	10	20	2.2%	-3.00 [-9.20, 3.20]
Hoffmann et al. 2021 [31]	157	18	24	151.4	17.7	38	1.7%	5.60 [-3.54, 14.74]
Driver et al. 2021 [12]	175.3	10	31	183.7	10.8	31	2.4%	-8.40 [-13.58, -3.22]
Doherty et al. 2021 [37]	142.43	9	12	139.78	11.4	12	1.9%	2.65 [-5.57, 10.87]
Subtotal (95% CI)			**101**			**115**	**9.7%**	**-0.94 [-6.39, 4.52]**
Heterogeneity: Tau² = 23.22; Chi² = 10.59, df = 4 (P = 0.03); I² = 62%								
Test for overall effect: Z = 0.34 (P = 0.74)								
Total (95% CI)			**1335**			**1373**	**100.0%**	**1.08 [-0.69, 2.85]**
Heterogeneity: Tau² = 26.68; Chi² = 244.51, df = 57 (P < 0.00001); I² = 77%								
Test for overall effect: Z = 1.19 (P = 0.23)								
Test for subgroup differences: Chi² = 0.54, df = 2 (P = 0.76), I² = 0%								

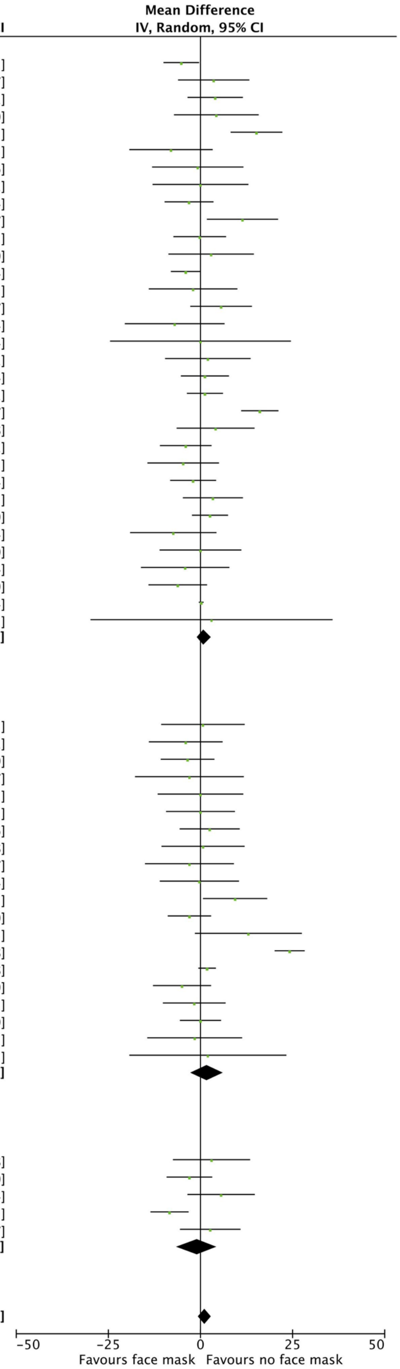


Fig. 2 Pooled analysis on the effect of face masks on heart rate. Effects for the subgroups are based on the grouping variables of different types (surgical mask vs FFP2/N95 vs cloth mask). *FFP2* filtering facepiece 2, *N95* N95 respirator, *WRVT* work rate at the ventilatory threshold

on variations in $PetO_2$ [3, 37, 39, 43, 48, 59]. In the meta-analysis, a significant reduction in $PetO_2$ was observed in those wearing surgical masks (MD − 3.17 mmHg, 95% CI − 4.87 to − 1.47; $p < 0.01$, $I^2 = 0\%$), FFP2/N95 respirators (MD − 5.10 mmHg, 95% CI − 9.27 to − 0.94; $p = 0.02$, $I^2 = 44\%$), and total effect (MD − 3.79 mmHg, 95% CI − 5.46 to − 2.12; $p < 0.01$, $I^2 = 21\%$), as shown in Fig. 3b. The SpO_2 was monitored in 30 studies [12–15, 18, 25, 27–29, 31, 33–37, 39, 42–45, 48–50, 52–54, 56–58, 60], and 27 studies were included in the meta-analysis with data extracted using WebPlotDigitizer [52]. A significant decrease was observed in those wearing surgical masks (MD − 0.59%, 95% CI − 0.87 to − 0.30; $p < 0.01$, $I^2 = 73\%$) and in the total effect (MD − 0.48%, 95% CI − 0.71 to − 0.26; $p < 0.01$,

Table 2 Subgroup analyses of effects of wearing face masks during exercise on physiological and psychological outcomes by exercise type

Outcome	*n*	Progressive exercise test			*n*	Steady-state exercise		
		MD or SMD (95% CI)	*p* value	I^2		MD or SMD (95% CI)	*p* value	I^2
Exercise performance[a]	34	− 0.34 (− 0.52 to − 0.15)	< 0.001	63%	7	0.16 (− 0.32 to 0.65)	0.51	90%
Heart rate (bpm)	31	− 0.74 (− 4.48 to 2.99)	0.7	86%	25	2.69 (1.10 to 4.28)	< 0.001	33%
VO_2[a]	16	− 0.68 (− 0.93 to − 0.43)	< 0.001	48%	3	− 0.57 (− 0.94 to − 0.21)	0.002	21%
SpO_2 (%)	27	− 0.60 (− 1.02 to − 0.18)	0.005	58%	19	− 0.41 (− 0.73 to − 0.10)	0.009	89%
$PetCO_2$ (mmHg)	10	4.15 (2.77 to 5.53)	< 0.001	43%	10	2.09 (0.93 to 3.25)	< 0.001	69%
RPE[a]	30	0.16 (0.05 to 0.28)	0.006	0%	13	0.51 (0.27 to 0.76)	< 0.001	58%
Dyspnea[a]	18	0.77 (0.53 to 1.01)	< 0.001	63%	8	0.64 (0.46 to 0.81)	< 0.001	0%
Fatigue level	5	1.91 (0.29 to 3.53)	0.02	81%	3	0.56 (− 0.37 to 1.48)	0.24	0%
Thermal sensation[a]	2	1.59 (0.55 to 2.64)	0.003	58%	5	0.35 (0.01 to 0.69)	0.04	0%
Blood lactate (mmol/L)	6	− 1.06 (− 1.69 to − 0.44)	< 0.001	0%	4	− 1.23 (− 0.40 to 2.86)	0.14	87%
Respiratory rate (breaths/min)	20	− 1.40 (− 4.02 to 1.23)	0.3	92%	13	− 0.26 (− 1.83 to 1.30)	0.74	76%
Minute ventilation (L/min)	16	− 18.11 (− 24.63 to − 11.58)	< 0.001	80%	3	− 0.07 (− 4.47 to 4.33)	0.98	29%
Tidal volume (L)	9	− 0.21 (− 0.31 to − 0.10)	< 0.001	0%	5	− 0.00 (− 0.12 to 0.12)	0.98	23%
VE/VCO_2	4	− 1.18 (− 2.42 to 0.06)	0.06	0%	3	− 2.39 (− 4.97 to 0.19)	0.07	78%

CI confidence intervals, *MD* mean differences, $PetCO_2$ end-tidal carbon dioxide partial pressure, *RPE* rating of perceived exertion, *SMD* standardized mean differences, SpO_2 oxygen saturation, VE/VCO_2 carbon dioxide ventilation equivalent, VO_2 oxygen uptake

[a]Outcome shown as SMD (95% CI)

$I^2 = 79\%$), while no change was observed in those wearing FFP2/N95 respirators ($p = 0.09$) and cloth masks ($p = 0.19$) (Fig. 3c). Moreover, a significant reduction in SpO_2 was observed in both progressive ($p < 0.01$) and steady-state ($p < 0.01$) exercise (Table 2). For the sensitivity analyses, the results for all three parameters remained consistent after removing either the studies with a high risk of bias or those examining children.

3.3.3 Carbon Dioxide Production and End-Tidal Partial Pressure

VCO_2 was examined in five studies [26, 30, 42, 43, 48], and a reduction in VCO_2 was observed among those wearing surgical masks and in terms of the total effect (Fig. 4a) (SMD − 0.74 and SMD − 0.77, respectively). Additionally, 13 studies reported $PetCO_2$ [13–15, 29, 37, 39, 43, 48, 52, 55, 56, 58, 59]. From the meta-analysis, a significant increase in $PetCO_2$ was observed in the total effect (MD 2.93 mmHg, 95% CI 2.01 to 3.86; $p < 0.01$, $I^2 = 65\%$) and in those wearing surgical masks (MD 2.32 mmHg) and FFP2/N95 respirators (MD 3.44 mmHg) (Fig. 4b). As shown in Table 2, similar results were observed for the sub-group analysis in terms of exercise type.

3.3.4 Lactate

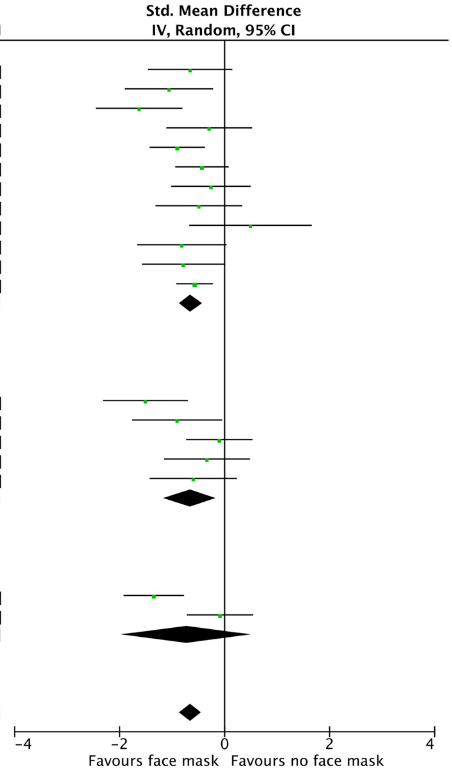
Lactate levels were reported in seven studies [3, 30, 34, 38, 42, 44, 53], but no significant changes were observed in the total effect (MD − 0.15 mmol/L, 95% CI − 1.19 to 0.89; $p = 0.78$, $I^2 = 82\%$). Similarly, no significant differences were observed for those wearing surgical masks ($p = 0.87$) and FFP2/N95 ($p = 0.06$), as shown in Fig. S1 (see ESM). Moreover, a significant reduction in lactate level was observed in progressive exercise tests ($p < 0.01$), with no change during steady-state ($p = 0.14$) exercise (Table 2).

3.3.5 Pulmonary Function

The pooled effect estimates for pulmonary function are shown in Fig. S2 (see ESM). Specifically, four indicators were involved: respiratory rate ($n = 19$) [3, 12–15, 29, 37, 39, 42, 43, 48, 50, 54–58, 61, 62], minute ventilation (VE) ($n = 12$) [3, 26, 30, 41–43, 48, 50, 51, 55, 58, 62], tidal volume (VT) ($n = 8$) [3, 41–43, 48, 55, 58, 62], and carbon dioxide ventilation equivalent (VE/VCO_2) ($n = 6$) [12, 41, 42, 48, 55, 62]. No significant effects were noted for respiratory rate ($p = 0.22$) when using face masks during exercise. Conversely, significant reductions occurred in VE (MD − 14.46 L/min), VT (MD − 0.11 L), and VE/VCO_2 (MD − 1.69) in those with masks compared with those with no masks during exercise. The results of the sub-group analysis by exercise type are shown in Table 2. A significant reduction was observed in VE ($p < 0.001$) and VT ($p < 0.001$) when only progressive exercise tests were included. After removing the studies with a high risk of bias or including children, the respiratory rate, VE, and VT results remained consistent.

(a)

Study or Subgroup	Face mask Mean	Face mask SD	Face mask Total	No face mask Mean	No face mask SD	No face mask Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.3.1 Surgical mask								
Alkan et al. 2021 (18–25y) [50]	26.37	4.9	13	30.09	6.02	13	4.6%	−0.66 [−1.45, 0.14]
Alkan et al. 2021 (45–64y) [50]	17.92	4.13	13	22.26	3.8	13	4.3%	−1.06 [−1.89, −0.23]
Egger et al. 2021 [30]	45	10.2	16	58.8	5.7	16	4.4%	−1.63 [−2.44, −0.81]
Fikenzer et al. 2020 [3]	37.9	6	12	39.7	5.8	12	4.5%	−0.29 [−1.10, 0.51]
Jesus et al. 2021 (WRVT + 25%) [62]	45.34	6.28	32	51.69	7.6	32	7.3%	−0.90 [−1.42, −0.38]
Jesus et al. 2021 (WRVT − 25%) [62]	30.23	3.37	32	31.83	3.93	32	7.6%	−0.43 [−0.93, 0.06]
Lässing et al. 2020 [42]	33.05	4.96	14	34.49	5.79	14	5.0%	−0.26 [−1.00, 0.49]
Mapelli et al. 2021 [43]	27.5	6.92	12	30.96	6.71	12	4.4%	−0.49 [−1.30, 0.32]
Otsuka et al. 2020 [51]	1,398.8	376.5	6	1,209.5	332.2	6	2.6%	0.49 [−0.66, 1.65]
Shui et al. 2022 [55]	1,345	325	12	1,653	401	12	4.2%	−0.81 [−1.65, 0.02]
Umutlu G et al. 2021 [26]	15.12	3.02	14	17.25	2.17	14	4.7%	−0.79 [−1.56, −0.01]
Zhang et al. 2021 [48]	24.3	4.96	71	27.3	5.47	71	9.8%	−0.57 [−0.91, −0.24]
Subtotal (95% CI)			**247**			**247**	**63.5%**	**−0.64 [−0.86, −0.42]**
Heterogeneity: $Tau^2 = 0.03$; $Chi^2 = 14.28$, df = 11 (P = 0.22); $I^2 = 23\%$								
Test for overall effect: Z = 5.69 (P < 0.00001)								
1.3.2 FFP2/N95								
Egger et al. 2021 [30]	47.6	8.5	16	58.8	5.7	16	4.5%	−1.51 [−2.31, −0.71]
Fikenzer et al. 2020 [3]	34.5	5.3	12	39.7	5.8	12	4.2%	−0.90 [−1.75, −0.06]
Kampert et al. 2021 [18]	38.1	8.6	20	39	8.9	20	6.1%	−0.10 [−0.72, 0.52]
Mapelli et al. 2021 [43]	28.24	8.79	12	30.96	6.71	12	4.5%	−0.34 [−1.14, 0.47]
Shui et al. 2022 [55]	1,417	363	12	1,653	401	12	4.4%	−0.60 [−1.42, 0.23]
Subtotal (95% CI)			**72**			**72**	**23.7%**	**−0.66 [−1.16, −0.16]**
Heterogeneity: $Tau^2 = 0.17$; $Chi^2 = 8.37$, df = 4 (P = 0.08); $I^2 = 52\%$								
Test for overall effect: Z = 2.59 (P = 0.010)								
1.3.3 Cloth mask								
Driver et al. 2021 [12]	32.2	9	30	43.9	8.1	30	6.7%	−1.35 [−1.91, −0.78]
Kampert et al. 2021 [18]	38.2	8.7	20	39	8.9	20	6.1%	−0.09 [−0.71, 0.53]
Subtotal (95% CI)			**50**			**50**	**12.9%**	**−0.73 [−1.96, 0.51]**
Heterogeneity: $Tau^2 = 0.70$; $Chi^2 = 8.67$, df = 1 (P = 0.003); $I^2 = 88\%$								
Test for overall effect: Z = 1.15 (P = 0.25)								
Total (95% CI)			**369**			**369**	**100.0%**	**−0.66 [−0.87, −0.45]**
Heterogeneity: $Tau^2 = 0.09$; $Chi^2 = 31.75$, df = 18 (P = 0.02); $I^2 = 43\%$								
Test for overall effect: Z = 6.14 (P < 0.00001)								
Test for subgroup differences: $Chi^2 = 0.02$, df = 2 (P = 0.99), $I^2 = 0\%$								



(b)

Study or Subgroup	Face mask Mean [mmHg]	Face mask SD [mmHg]	Face mask Total	No face mask Mean [mmHg]	No face mask SD [mmHg]	No face mask Total	Weight	Mean Difference IV, Random, 95% CI
1.4.1 Surgical mask								
Ade et al. 2021 [39]	118	10	5	129	12	5	1.5%	−11.00 [−24.69, 2.69]
Doherty et al. 2021 [37]	114.6	8.05	12	114.38	7.17	12	6.6%	0.22 [−5.88, 6.32]
Fikenzer et al. 2020 [3]	116	23.7	12	107	20.5	12	0.9%	9.00 [−8.73, 26.73]
Mapelli et al. 2021 [43]	115	3	12	118	3	12	25.3%	−3.00 [−5.40, −0.60]
Rudi et al. 2021 [59]	79.1	7.5	20	84	6.7	20	11.3%	−4.90 [−9.31, −0.49]
Zhang et al. 2021 [48]	112.2	11	71	115.7	9.75	71	16.5%	−3.50 [−6.92, −0.08]
Subtotal (95% CI)			**132**			**132**	**62.0%**	**−3.17 [−4.87, −1.47]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 4.90$, df = 5 (P = 0.43); $I^2 = 0\%$								
Test for overall effect: Z = 3.65 (P = 0.0003)								
1.4.2 FFP2/N95								
Ade et al. 2021 [39]	114	11	5	129	12	5	1.3%	−15.00 [−29.27, −0.73]
Fikenzer et al. 2020 [3]	116	23.2	12	107	20.5	12	0.9%	9.00 [−8.52, 26.52]
Mapelli et al. 2021 [43]	114	3	12	118	3	12	25.3%	−4.00 [−6.40, −1.60]
Rudi et al. 2021 [59]	77.3	8.2	20	84	6.7	20	10.4%	−6.70 [−11.34, −2.06]
Subtotal (95% CI)			**49**			**49**	**38.0%**	**−5.10 [−9.27, −0.94]**
Heterogeneity: $Tau^2 = 7.17$; $Chi^2 = 5.38$, df = 3 (P = 0.15); $I^2 = 44\%$								
Test for overall effect: Z = 2.40 (P = 0.02)								
Total (95% CI)			**181**			**181**	**100.0%**	**−3.79 [−5.46, −2.12]**
Heterogeneity: $Tau^2 = 1.38$; $Chi^2 = 11.37$, df = 9 (P = 0.25); $I^2 = 21\%$								
Test for overall effect: Z = 4.44 (P < 0.00001)								
Test for subgroup differences: $Chi^2 = 0.71$, df = 1 (P = 0.40), $I^2 = 0\%$								

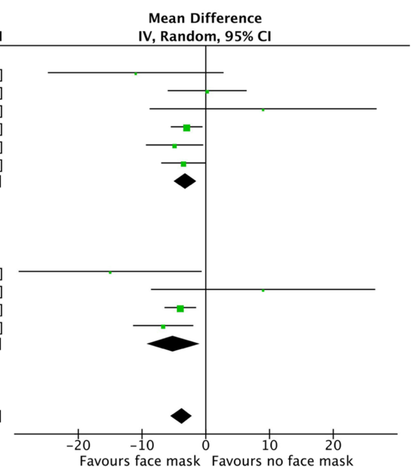


Fig. 3 Pooled analysis on the effect of face masks on **a** VO_2, **b** $PetO_2$, and **c** SpO_2. Effects for the subgroups are based on the grouping variables of different types (surgical mask vs FFP2/N95 vs cloth mask). *FFP2* filtering facepiece 2, *N95* N95 respirator, *$PetO_2$* end-tidal oxygen partial pressure, *SpO_2* oxygen saturation, *VO_2* oxygen uptake, *WRVT* work rate at the ventilatory threshold

(c)

Study or Subgroup	Face mask Mean [%]	Face mask SD [%]	Face mask Total	No face mask Mean [%]	No face mask SD [%]	No face mask Total	Weight	Mean Difference IV, Random, 95% CI
1.5.1 Surgical mask								
Ade et al. 2021 [39]	97	1	5	98	1	5	1.9%	−1.00 [−2.24, 0.24]
Akgul et al. 2021 [49]	97.02	0.09	30	97.93	0.1	30	4.5%	−0.91 [−0.96, −0.86]
Alkan et al. 2021 (18–25y) [50]	96.31	2.78	13	97	1.87	13	1.2%	−0.69 [−2.51, 1.13]
Alkan et al. 2021 (45–64y) [50]	97.15	1.21	13	97.15	0.69	13	3.0%	0.00 [−0.76, 0.76]
Bar–on et al. 2021 (Brisk walk) [52]	96.71	0.94	21	98.25	0.85	21	3.6%	−1.54 [−2.08, −1.00]
Cabanillas–Barea et al. 2021 [25]	94.88	8.22	50	95.88	4.74	50	0.6%	−1.00 [−3.63, 1.63]
Dirol et al. 2021 [13]	97.56	0.92	100	97.8	0.86	100	4.2%	−0.24 [−0.49, 0.01]
Doherty et al. 2021 [37]	98.54	0.73	12	98.67	1.29	12	2.8%	−0.13 [−0.97, 0.71]
Epstein et al. 2021 [14]	97.69	1.62	16	98.13	1.09	16	2.5%	−0.44 [−1.40, 0.52]
Fukushi et al. 2021 [36]	96	0.93	24	95.25	2.4	24	2.3%	0.75 [−0.28, 1.78]
Hoffmann et al. 2021 [31]	96.9	1.1	14	96.9	1.4	38	3.1%	0.00 [−0.73, 0.73]
Hua et al. 2021 [35]	95.2	1.13	23	96.4	0.89	23	3.4%	−1.20 [−1.79, −0.61]
Lässing et al. 2020 [42]	95.32	0.83	14	95.22	0.71	14	3.5%	0.10 [−0.47, 0.67]
Mapelli et al. 2021 [43]	96.5	1.2	12	97.3	1.2	12	2.5%	−0.80 [−1.76, 0.16]
Ng et al. 2022 [53]	90	6	8	92	3	8	0.2%	−2.00 [−6.65, 2.65]
Pimenta et al. 2021 [60]	92.5	3.9	12	94.5	2.7	12	0.6%	−2.00 [−4.68, 0.68]
Poon et al. 2021 [44]	97	1.4	13	97.5	0.8	13	2.7%	−0.50 [−1.38, 0.38]
Shaw et al. 2020 [45]	96	3	14	96	4	14	0.6%	0.00 [−2.62, 2.62]
Shaw et al. 2021 [28]	88.38	6.01	26	88.86	5.92	26	0.4%	−0.48 [−3.72, 2.76]
Steinhilber et al. 2022 (130 W) [54]	97.42	3.38	39	97.3	3.74	39	1.4%	0.12 [−1.46, 1.70]
Steinhilber et al. 2022 (150 W) [54]	98.11	3.02	39	97.45	4.84	39	1.2%	0.66 [−1.13, 2.45]
Tornero–Aguilera et al. 2021 (400m) [34]	96.7	3.06	72	98.1	1.31	72	3.0%	−1.40 [−2.17, −0.63]
Tornero–Aguilera et al. 2021 (50m) [34]	95.2	6.02	72	97.8	1.49	72	1.6%	−2.60 [−4.03, −1.17]
Zhang et al. 2021 [48]	95.3	9.25	71	95.3	8.72	71	0.5%	0.00 [−2.96, 2.96]
Subtotal (95% CI)			**713**			**737**	**51.3%**	**−0.59 [−0.87, −0.30]**
Heterogeneity: Tau² = 0.21; Chi² = 83.87, df = 23 (P < 0.00001); I² = 73%								
Test for overall effect: Z = 4.05 (P < 0.0001)								
1.5.2 FFP2/N95								
Ade et al. 2021 [39]	98	1	5	98	1	5	1.9%	0.00 [−1.24, 1.24]
Cabanillas–Barea et al. 2021 [25]	96.94	2.6	50	95.88	4.74	50	1.5%	1.06 [−0.44, 2.56]
Epstein et al. 2021 [14]	97.63	1.26	16	98.13	1.09	16	2.8%	−0.50 [−1.32, 0.32]
Goh et al. 2019 [29]	99.2	0.65	106	99.2	0.81	106	4.3%	0.00 [−0.20, 0.20]
Hua et al. 2021 [35]	94.5	1.34	23	96.4	0.89	23	3.2%	−1.90 [−2.56, −1.24]
Kampert et al. 2021 [18]	93.4	4.1	20	96.2	3.7	20	0.7%	−2.80 [−5.22, −0.38]
Kim et al. 2013 [15]	97.7	1.3	20	97.8	1	20	3.1%	−0.10 [−0.82, 0.62]
Kim et al. 2016 [56]	97.8	0.6	12	97.9	1.1	12	3.1%	−0.10 [−0.81, 0.61]
Mapelli et al. 2021 [43]	95.1	3.1	12	97.3	1.2	12	1.1%	−2.20 [−4.08, −0.32]
Pimenta et al. 2021 [60]	91.3	4	12	94.5	2.7	12	0.6%	−3.20 [−5.93, −0.47]
Roberge et al. 2010 (1.7 m/h) [58]	98.1	0.9	10	98.5	0.8	10	3.0%	−0.40 [−1.15, 0.35]
Roberge et al. 2010 (2.5 m/h) [58]	98.4	0.7	10	98.5	0.8	10	3.2%	−0.10 [−0.76, 0.56]
Rosa et al. 2021 (High intensity) [33]	96.7	1.6	17	96.8	1.3	17	2.4%	−0.10 [−1.08, 0.88]
Rosa et al. 2021 (Moderate intensity) [33]	97	1.4	17	97.4	1.5	17	2.4%	−0.40 [−1.38, 0.58]
Steinhilber et al. 2022 (130 W) [54]	98.29	2.94	39	97.3	3.74	39	1.5%	0.99 [−0.50, 2.48]
Steinhilber et al. 2022 (150 W) [54]	98.66	2.17	39	97.45	4.84	39	1.3%	1.21 [−0.45, 2.87]
Subtotal (95% CI)			**408**			**408**	**36.4%**	**−0.35 [−0.75, 0.05]**
Heterogeneity: Tau² = 0.38; Chi² = 52.14, df = 15 (P < 0.00001); I² = 71%								
Test for overall effect: Z = 1.71 (P = 0.09)								
1.5.3 Cloth mask								
Doherty et al. 2021 [37]	98.33	1.64	12	98.67	1.29	12	2.0%	−0.34 [−1.52, 0.84]
Driver et al. 2021 [12]	93.4	3.1	31	95.1	2.4	31	1.7%	−1.70 [−3.08, −0.32]
Fukushi et al. 2021 [36]	96	2.4	24	96.5	2.4	24	1.7%	−0.50 [−1.86, 0.86]
Hoffmann et al. 2021 [31]	97	1.5	24	96.9	1.4	38	3.0%	0.10 [−0.65, 0.85]
Kampert et al. 2021 [18]	92.9	3.8	20	96.2	3.7	20	0.8%	−3.30 [−5.62, −0.98]
Shaw et al. 2020 [45]	95	3	14	96	4	14	0.6%	−1.00 [−3.62, 1.62]
Steinhilber et al. 2022 (130 W) [54]	97.9	4.03	39	97.3	3.74	39	1.2%	0.60 [−1.13, 2.33]
Steinhilber et al. 2022 (150 W) [54]	98.18	2.71	39	97.45	4.84	39	1.2%	0.73 [−1.01, 2.47]
Subtotal (95% CI)			**203**			**217**	**12.3%**	**−0.50 [−1.23, 0.24]**
Heterogeneity: Tau² = 0.52; Chi² = 14.18, df = 7 (P = 0.05); I² = 51%								
Test for overall effect: Z = 1.32 (P = 0.19)								
Total (95% CI)			**1324**			**1362**	**100.0%**	**−0.48 [−0.71, −0.26]**
Heterogeneity: Tau² = 0.30; Chi² = 227.10, df = 47 (P < 0.00001); I² = 79%								
Test for overall effect: Z = 4.17 (P < 0.0001)								
Test for subgroup differences: Chi² = 0.88, df = 2 (P = 0.64), I² = 0%								

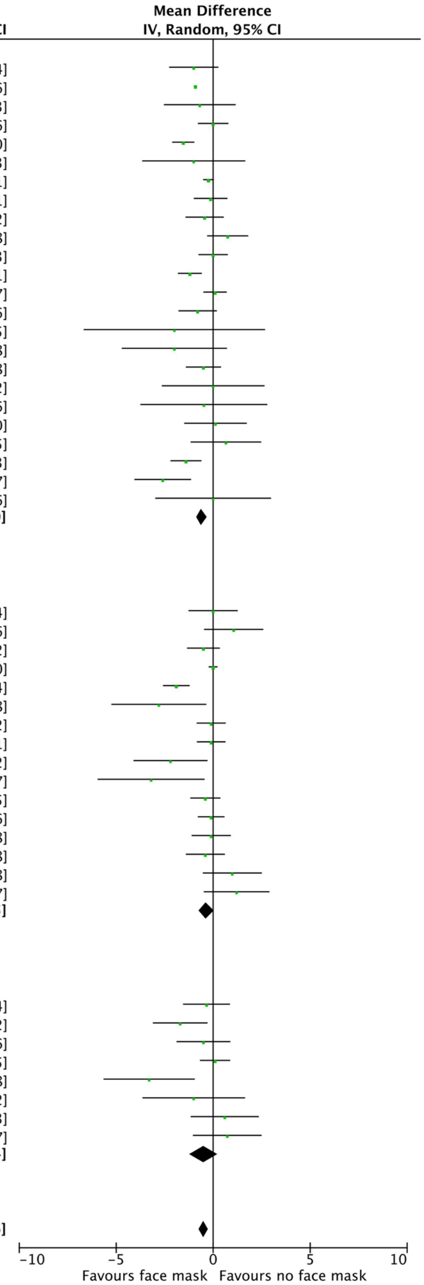


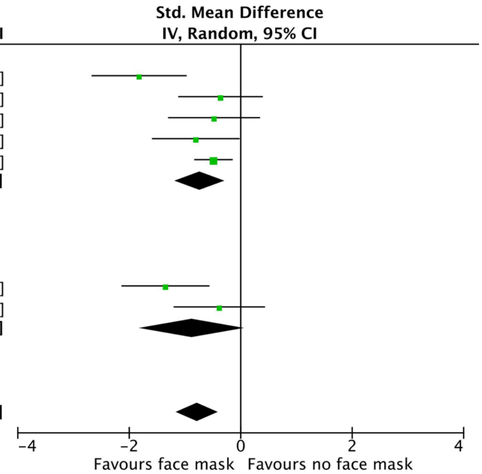
Fig. 3 (continued)

3.4 Psychological Outcomes

For the psychological outcomes, RPE was the most commonly used scale reported in 27 studies [12, 14, 18, 27, 28, 30–34, 36, 38, 41, 42, 44–48, 51, 52, 54, 56–60]. Two studies were excluded because of the unavailability of raw data [27, 48]. The RPE was significantly higher in those wearing surgical masks (SMD 0.36, 95% CI 0.21–0.52; $p<0.01$; $I^2=30\%$), while no effect was observed in those with FFP2/N95 respirators ($p=0.06$) or cloth masks ($p=0.21$), as shown in Fig. 5a. Additionally, 14 studies reported on dyspnea [12, 25, 37–39, 43, 48, 50, 52–56, 60], five reported on fatigue level [3, 18, 40, 41, 47], and six reported on thermal sensation [3, 18, 40, 47, 56, 57]. This meta-analysis establishes that wearing face masks during exercise results in significantly higher dyspnea (SMD 0.72), fatigue level (MD 1.34), and thermal sensation (SMD 0.67) in participants (Fig. 5b-d). In addition, as shown in Table 2, similar

(a)

Study or Subgroup	Face mask Mean	SD	Total	No face mask Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.6.1 Surgical mask								
Egger et al. 2021 [30]	49.7	13.8	16	70.6	7.7	16	11.9%	−1.82 [−2.66, −0.98]
Lässing et al. 2020 [42]	2,575	310	14	2,685	278	14	13.6%	−0.36 [−1.11, 0.39]
Mapelli et al. 2021 [43]	2,217	691	12	2,578	763	12	12.4%	−0.48 [−1.29, 0.33]
Umutlu G et al. 2021 [26]	13.77	2.74	14	15.67	1.72	14	13.1%	−0.81 [−1.58, −0.03]
Zhang et al. 2021 [48]	1,873	578.7	71	2,169.9	627.8	71	23.5%	−0.49 [−0.82, −0.16]
Subtotal (95% CI)			**127**			**127**	**74.5%**	**−0.74 [−1.19, −0.28]**
Heterogeneity: $Tau^2 = 0.14$; $Chi^2 = 9.23$, df = 4 (P = 0.06); $I^2 = 57\%$								
Test for overall effect: Z = 3.19 (P = 0.001)								
1.6.2 FFP2/N95								
Egger et al. 2021 [30]	56.3	12.4	16	70.6	7.7	16	13.0%	−1.35 [−2.13, −0.57]
Mapelli et al. 2021 [43]	2,268	794	12	2,578	763	12	12.5%	−0.38 [−1.19, 0.42]
Subtotal (95% CI)			**28**			**28**	**25.5%**	**−0.87 [−1.82, 0.07]**
Heterogeneity: $Tau^2 = 0.30$; $Chi^2 = 2.85$, df = 1 (P = 0.09); $I^2 = 65\%$								
Test for overall effect: Z = 1.81 (P = 0.07)								
Total (95% CI)			**155**			**155**	**100.0%**	**−0.77 [−1.15, −0.39]**
Heterogeneity: $Tau^2 = 0.13$; $Chi^2 = 12.74$, df = 6 (P = 0.05); $I^2 = 53\%$								
Test for overall effect: Z = 3.97 (P < 0.0001)								
Test for subgroup differences: $Chi^2 = 0.07$, df = 1 (P = 0.80), $I^2 = 0\%$								



(b)

Study or Subgroup	Face mask Mean [mmHg]	SD [mmHg]	Total	No face mask Mean [mmHg]	SD [mmHg]	Total	Weight	Mean Difference IV, Random, 95% CI
1.7.1 Surgical mask								
Ade et al. 2021 [39]	37	7	5	29	9	5	0.8%	8.00 [−1.99, 17.99]
Bar−on et al. 2021 (Brisk walk) [52]	42.41	1.59	21	39.7	2.29	21	9.4%	2.71 [1.52, 3.90]
Dirol et al. 2021 [13]	38.73	3.22	100	37.21	3.33	100	10.1%	1.52 [0.61, 2.43]
Doherty et al. 2021 [37]	38.79	5.16	12	39.5	4.93	12	3.6%	−0.71 [−4.75, 3.33]
Epstein et al. 2021 [14]	40.19	3.99	16	36.31	4.83	16	5.0%	3.88 [0.81, 6.95]
Mapelli et al. 2021 [43]	35.13	3.09	12	33.04	4.28	12	5.1%	2.09 [−0.90, 5.08]
Rudi et al. 2021 [59]	33.3	4	20	29	3.1	20	6.8%	4.30 [2.08, 6.52]
Shui et al. 2022 [55]	46.8	3.8	12	45.9	3.7	12	5.1%	0.90 [−2.10, 3.90]
Zhang et al. 2021 [48]	41.6	10.2	11	38.8	9.7	11	1.1%	2.80 [−5.52, 11.12]
Subtotal (95% CI)			**209**			**209**	**47.0%**	**2.32 [1.38, 3.26]**
Heterogeneity: $Tau^2 = 0.52$; $Chi^2 = 11.46$, df = 8 (P = 0.18); $I^2 = 30\%$								
Test for overall effect: Z = 4.85 (P < 0.00001)								
1.7.2 FFP2/N95								
Ade et al. 2021 [39]	39	7	5	29	9	5	0.8%	10.00 [0.01, 19.99]
Epstein et al. 2021 [14]	43.31	3.96	16	36.31	4.83	16	5.0%	7.00 [3.94, 10.06]
Goh et al. 2019 [29]	32	2.8	106	28.2	2.8	106	10.4%	3.80 [3.05, 4.55]
Kim et al. 2013 [15]	42.7	3.3	20	39.7	3.8	20	6.8%	3.00 [0.79, 5.21]
Kim et al. 2016 [56]	41.3	2.4	12	40.9	2.4	12	7.5%	0.40 [−1.52, 2.32]
Mapelli et al. 2021 [43]	36.26	3.94	12	33.04	4.28	12	4.6%	3.22 [−0.07, 6.51]
Roberge et al. 2010 (1.7 m/h) [58]	39.7	6	10	40.7	3.5	10	3.2%	−1.00 [−5.31, 3.31]
Roberge et al. 2010 (2.5 m/h) [58]	42	5.6	10	40.8	3.2	10	3.6%	1.20 [−2.80, 5.20]
Rudi et al. 2021 [59]	35.8	4.9	20	29	3.1	20	6.0%	6.80 [4.26, 9.34]
Shui et al. 2022 [55]	49.7	4.1	12	45.9	3.7	12	4.9%	3.80 [0.68, 6.92]
Subtotal (95% CI)			**223**			**223**	**53.0%**	**3.44 [1.96, 4.91]**
Heterogeneity: $Tau^2 = 3.21$; $Chi^2 = 29.44$, df = 9 (P = 0.0005); $I^2 = 69\%$								
Test for overall effect: Z = 4.58 (P < 0.00001)								
Total (95% CI)			**432**			**432**	**100.0%**	**2.93 [2.01, 3.86]**
Heterogeneity: $Tau^2 = 1.97$; $Chi^2 = 51.03$, df = 18 (P < 0.0001); $I^2 = 65\%$								
Test for overall effect: Z = 6.24 (P < 0.00001)								
Test for subgroup differences: $Chi^2 = 1.57$, df = 1 (P = 0.21), $I^2 = 36.3\%$								

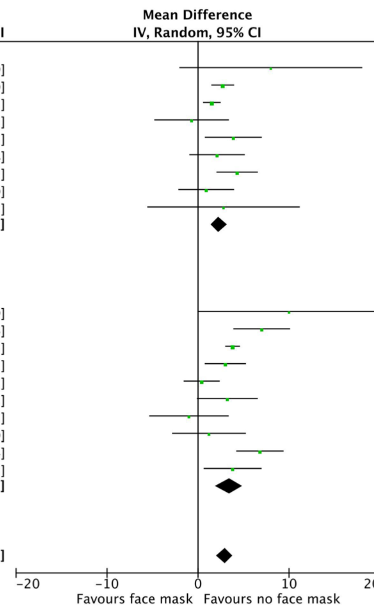


Fig. 4 Pooled analysis on the effect of face masks on **a** VCO_2 and **b** $PetCO_2$. Effects for the subgroups are based on the grouping variables of different types (surgical mask vs FFP2/N95 vs cloth mask). *FFP2* filtering facepiece 2, *N95* N95 respirator, *$PetCO_2$* end-tidal carbon dioxide partial pressure, *VCO_2* carbon dioxide production

results were observed for the sub-group analysis in terms of exercise type. The results remained consistent for both RPE and thermal sensation after removing either the studies with a high risk of bias or those including children.

3.5 Exercise Performance

A total of 25 studies evaluated exercise performance, and 23 studies were included in the meta-analysis, as data were unavailable for two studies [27, 39]. Most studies used power output ($n=13$) [3, 28, 30, 41–43, 45, 48, 51, 53–55, 59], while others used test duration ($n=6$) [12, 14, 18, 32, 50, 60], exercise speed ($n=2$) [34, 35], and exercise distance ($n=2$) [13, 25]. WebPlotDigitizer was used for data extraction from one study [55]. In the meta-analysis, significant reductions were observed in exercise performance between those wearing and those not wearing face masks (SMD −0.23, 95% CI −0.41 to −0.04; $p=0.02$, $I^2=77\%$), as shown in Fig. 6. In the sub-group analysis, a significant decrease was noted in those wearing FFP2/N95 respirators (SMD −0.42, 95% CI −0.76 to −0.08; $p=0.02$, $I^2=72\%$), whereas no change was noted in those wearing surgical

(a)

Study or Subgroup	Face mask Mean	SD	Total	No face mask Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.8.1 Surgical mask								
Bar–on et al. 2021 (Brisk walk) [52]	4.3	1.6	21	3.1	1.43	21	2.2%	0.78 [0.15, 1.41]
Bar–on et al. 2021 (Slow walk) [52]	1.8	0.94	21	1.3	0.59	21	2.3%	0.63 [0.00, 1.25]
Boldrini et al. 2020 [38]	6.2	1.3	25	6	1.8	25	2.7%	0.13 [−0.43, 0.68]
Egger et al. 2021 [30]	7.1	1.6	16	6.6	1.3	16	1.9%	0.33 [−0.36, 1.03]
Epstein et al. 2021 [14]	10	0.01	16	10	0.01	16	1.9%	0.00 [−0.69, 0.69]
Fukushi et al. 2021 [36]	6	1.93	24	5	1.99	24	2.6%	0.50 [−0.07, 1.08]
Hoffmann et al. 2021 [31]	15.3	1.6	14	12.9	1.8	38	2.1%	1.35 [0.68, 2.02]
Lässing et al. 2020 [42]	6.9	1.1	14	6.6	1.1	14	1.7%	0.26 [−0.48, 1.01]
Li et al. 2021 (Females) [41]	17.2	1.3	5	17.4	0.89	5	0.7%	−0.16 [−1.41, 1.08]
Li et al. 2021 (Males) [41]	17	1.73	5	17.8	0.84	5	0.7%	−0.53 [−1.81, 0.74]
Otsuka et al. 2020 [51]	6.3	2.2	6	5	1.8	6	0.8%	0.60 [−0.57, 1.77]
Pimenta et al. 2021 [60]	16.4	2.4	12	15.3	1.7	12	1.5%	0.51 [−0.30, 1.33]
Poon et al. 2021 [44]	15.5	1.5	13	14.2	2.1	13	1.6%	0.69 [−0.11, 1.49]
Roberge et al. 2012 [57]	11.2	1.7	20	10.6	1.8	20	2.3%	0.34 [−0.29, 0.96]
Rudi et al. 2021 [59]	14.5	2.7	20	14.2	1.8	20	2.3%	0.13 [−0.49, 0.75]
Shaw et al. 2020 [45]	9.9	0.4	14	9.9	0.5	14	1.8%	0.00 [−0.74, 0.74]
Shaw et al. 2021 (Female) [28]	6.64	3.02	5	4.83	3.19	5	0.7%	0.53 [−0.75, 1.80]
Shaw et al. 2021 (Male) [28]	7.17	1.47	21	7.07	1.63	21	2.4%	0.06 [−0.54, 0.67]
Steinhilber et al. 2022 (130 W) [54]	3.8	1.67	39	3.51	1.25	39	3.5%	0.19 [−0.25, 0.64]
Steinhilber et al. 2022 (150 W) [54]	4.87	1.7	39	4.47	1.35	39	3.5%	0.26 [−0.19, 0.70]
Tornero–Aguilera et al. 2021 (400m) [34]	18.7	1.65	72	17.5	1.82	72	4.7%	0.69 [0.35, 1.02]
Tornero–Aguilera et al. 2021 (50m) [34]	13.4	2.9	72	13.7	3.75	72	4.8%	−0.09 [−0.42, 0.24]
Wong et al. 2020 [46]	12.7	2.1	23	10.8	2.2	23	2.4%	0.87 [0.26, 1.48]
Yoshihara et al. 2021 [47]	12.3	2.5	12	11.7	1.8	12	1.5%	0.27 [−0.54, 1.07]
Subtotal (95% CI)			**529**			**553**	**52.6%**	**0.36 [0.21, 0.52]**
Heterogeneity: Tau² = 0.04; Chi² = 33.08, df = 23 (P = 0.08); I² = 30%								
Test for overall effect: Z = 4.57 (P < 0.00001)								
1.8.2 FFP2/N95								
Egger et al. 2021 [30]	6.9	1.5	16	6.6	1.3	16	1.9%	0.21 [−0.49, 0.90]
Epstein et al. 2021 [14]	10	0.01	16	10	0.01	16	1.9%	0.00 [−0.69, 0.69]
Kampert et al. 2021 [18]	9.5	0.8	20	9.6	0.9	20	2.3%	−0.12 [−0.74, 0.51]
Kim et al. 2016 [56]	9.9	2.1	12	9.3	2	12	1.5%	0.28 [−0.52, 1.09]
Pimenta et al. 2021 [60]	17.1	2.4	12	15.3	1.7	12	1.4%	0.84 [−0.01, 1.68]
Roberge et al. 2010 (1.7 m/h) [58]	0.83	1.3	10	0.5	0.85	10	1.3%	0.29 [−0.59, 1.17]
Roberge et al. 2010 (2.5 m/h) [58]	1.11	1.3	10	1.05	1.16	10	1.3%	0.05 [−0.83, 0.92]
Rosa et al. 2021 (High intensity) [33]	8.41	1	17	8.2	1.1	17	2.0%	0.20 [−0.48, 0.87]
Rosa et al. 2021 (Moderate intensity) [33]	8.4	1.4	17	8.1	1.05	17	2.0%	0.24 [−0.44, 0.91]
Rudi et al. 2021 [59]	15.2	2.6	20	14.2	1.8	20	2.3%	0.44 [−0.19, 1.07]
Steinhilber et al. 2022 (130 W) [54]	3.59	1.83	39	3.51	1.25	39	3.5%	0.05 [−0.39, 0.49]
Steinhilber et al. 2022 (150 W) [54]	4.59	1.83	39	4.47	1.35	39	3.5%	0.07 [−0.37, 0.52]
Yoshihara et al. 2021 [47]	12.3	2.8	12	11.7	1.8	12	1.5%	0.25 [−0.56, 1.05]
Subtotal (95% CI)			**240**			**240**	**26.8%**	**0.17 [−0.01, 0.35]**
Heterogeneity: Tau² = 0.00; Chi² = 4.92, df = 12 (P = 0.96); I² = 0%								
Test for overall effect: Z = 1.85 (P = 0.06)								
1.8.3 Cloth mask								
Dantas et al. 2021 [32]	49.14	22.59	10	33.62	8.79	10	1.2%	0.87 [−0.06, 1.79]
Driver et al. 2021 [12]	16.9	3	30	16.8	3	30	3.0%	0.03 [−0.47, 0.54]
Fukushi et al. 2021 [36]	6.5	2.05	24	5	1.99	24	2.5%	0.73 [0.14, 1.32]
Hoffmann et al. 2021 [31]	14.6	1.5	24	12.9	1.8	38	2.8%	0.99 [0.45, 1.53]
Kampert et al. 2021 [18]	9.3	1	20	9.6	0.9	20	2.3%	−0.31 [−0.93, 0.31]
Shaw et al. 2020 [45]	9.7	0.6	14	9.9	0.5	14	1.7%	−0.35 [−1.10, 0.40]
Steinhilber et al. 2022 (130 W) [54]	3.42	1.39	39	3.51	1.25	39	3.5%	−0.07 [−0.51, 0.38]
Steinhilber et al. 2022 (150 W) [54]	4.51	1.66	39	4.47	1.35	39	3.5%	0.03 [−0.42, 0.47]
Subtotal (95% CI)			**200**			**214**	**20.6%**	**0.22 [−0.13, 0.57]**
Heterogeneity: Tau² = 0.16; Chi² = 20.40, df = 7 (P = 0.005); I² = 66%								
Test for overall effect: Z = 1.25 (P = 0.21)								
Total (95% CI)			**969**			**1007**	**100.0%**	**0.28 [0.17, 0.39]**
Heterogeneity: Tau² = 0.04; Chi² = 61.76, df = 44 (P = 0.04); I² = 29%								
Test for overall effect: Z = 4.98 (P < 0.00001)								
Test for subgroup differences: Chi² = 2.59, df = 2 (P = 0.27), I² = 22.8%								

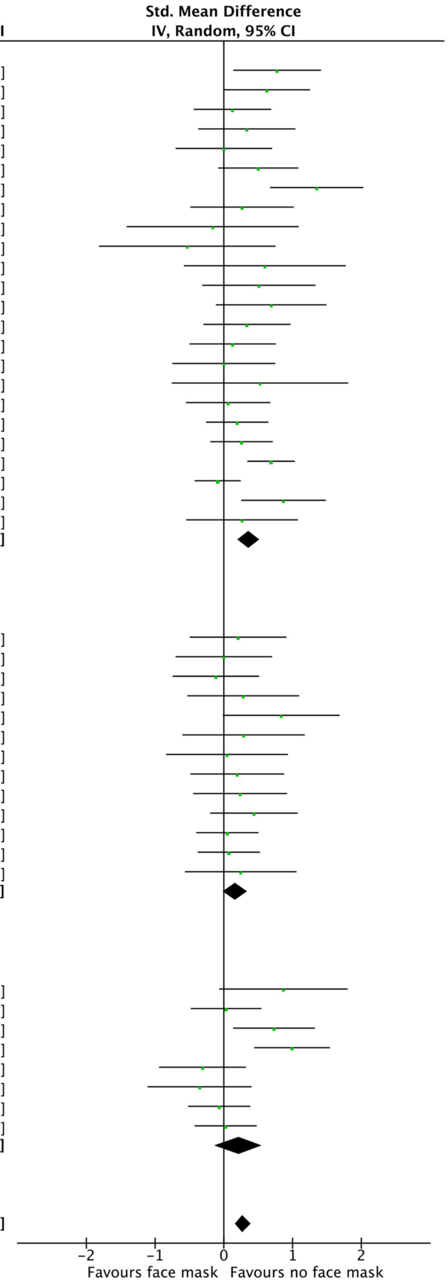
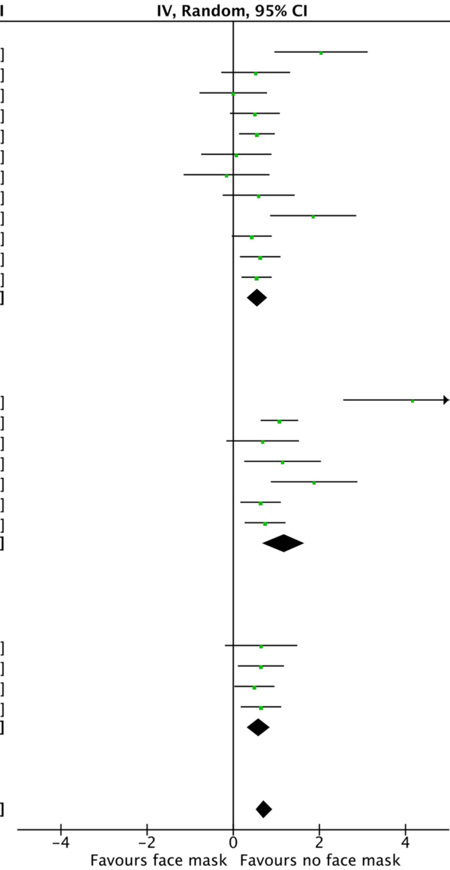


Fig. 5 Pooled analysis on the effect of face masks on psychological perceptual response: **a** RPE, **b** dyspnea, **c** fatigue level, and **d** thermal sensation. Effects for the subgroups are based on the grouping variables of different types (surgical mask vs FFP2/N95 vs cloth mask). *FFP2* filtering facepiece 2, *N95* N95 respirator, *RPE* rate of perceived exertion

(b)

Study or Subgroup	Face mask Mean	SD	Total	No face mask Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.9.1 Surgical mask								
Ade et al. 2021 [39]	10.96	0.87	11	9.19	0.8	11	2.4%	2.04 [0.97, 3.11]
Alkan et al. 2021 (18–25y) [50]	6.15	1.68	13	5.23	1.74	13	3.6%	0.52 [−0.26, 1.30]
Alkan et al. 2021 (45–64y) [50]	5.38	2.36	13	5.38	2.29	13	3.7%	0.00 [−0.77, 0.77]
Boldrini et al. 2020 [38]	5.7	2	25	4.6	2.3	25	5.0%	0.50 [−0.06, 1.07]
Cabanillas-Barea et al. 2021 [25]	2.48	1.71	50	1.54	1.69	50	6.3%	0.55 [0.15, 0.95]
Doherty et al. 2021 [37]	1.32	1.52	12	1.22	1.14	12	3.5%	0.07 [−0.73, 0.87]
Ng et al. 2022 [53]	9.7	0.7	8	9.8	0.5	8	2.7%	−0.16 [−1.14, 0.83]
Pimenta et al. 2021 [60]	6.8	1.9	12	5.7	1.7	12	3.4%	0.59 [−0.23, 1.41]
Shui et al. 2022 [55]	6.4	1.83	12	3.06	1.64	12	2.7%	1.86 [0.87, 2.84]
Steinhilber et al. 2022 (130 W) [54]	3.89	1.7	39	3.19	1.52	39	5.9%	0.43 [−0.02, 0.88]
Steinhilber et al. 2022 (150 W) [54]	5.12	1.92	39	3.97	1.71	39	5.8%	0.63 [0.17, 1.08]
Zhang et al. 2021 [48]	5.69	1.62	71	4.78	1.72	71	6.8%	0.54 [0.21, 0.88]
Subtotal (95% CI)			**305**			**305**	**51.6%**	**0.56 [0.32, 0.80]**
Heterogeneity: $Tau^2 = 0.07$; $Chi^2 = 19.95$, df = 11 (P = 0.05); $I^2 = 45\%$								
Test for overall effect: Z = 4.59 (P < 0.00001)								
1.9.2 FFP2/N95								
Ade et al. 2021 [39]	12.92	0.92	11	9.19	0.8	11	1.3%	4.16 [2.57, 5.76]
Cabanillas-Barea et al. 2021 [25]	3.52	1.97	50	1.54	1.69	50	6.1%	1.07 [0.65, 1.49]
Kim et al. 2016 [56]	2.2	0.6	12	1.7	0.8	12	3.4%	0.68 [−0.14, 1.51]
Pimenta et al. 2021 [60]	7.6	1.5	12	5.7	1.7	12	3.1%	1.14 [0.27, 2.02]
Shui et al. 2022 [55]	6.82	2.19	12	3.06	1.64	12	2.7%	1.88 [0.89, 2.87]
Steinhilber et al. 2022 (130 W) [54]	4.3	1.92	39	3.19	1.52	39	5.8%	0.63 [0.18, 1.09]
Steinhilber et al. 2022 (150 W) [54]	5.34	1.95	39	3.97	1.71	39	5.8%	0.74 [0.28, 1.20]
Subtotal (95% CI)			**175**			**175**	**28.1%**	**1.18 [0.69, 1.67]**
Heterogeneity: $Tau^2 = 0.28$; $Chi^2 = 22.51$, df = 6 (P = 0.0010); $I^2 = 73\%$								
Test for overall effect: Z = 4.75 (P < 0.00001)								
1.9.3 Cloth mask								
Doherty et al. 2021 [37]	2.06	1.36	12	1.22	1.14	12	3.4%	0.65 [−0.18, 1.47]
Driver et al. 2021 [12]	7.2	2.9	30	5.5	2.3	30	5.3%	0.64 [0.12, 1.16]
Steinhilber et al. 2022 (130 W) [54]	3.96	1.59	39	3.19	1.52	39	5.8%	0.49 [0.04, 0.94]
Steinhilber et al. 2022 (150 W) [54]	5.12	1.83	39	3.97	1.71	39	5.8%	0.64 [0.19, 1.10]
Subtotal (95% CI)			**120**			**120**	**20.3%**	**0.59 [0.33, 0.85]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 0.29$, df = 3 (P = 0.96); $I^2 = 0\%$								
Test for overall effect: Z = 4.48 (P < 0.00001)								
Total (95% CI)			**600**			**600**	**100.0%**	**0.72 [0.53, 0.92]**
Heterogeneity: $Tau^2 = 0.12$; $Chi^2 = 51.74$, df = 22 (P = 0.0003); $I^2 = 57\%$								
Test for overall effect: Z = 7.27 (P < 0.00001)								
Test for subgroup differences: $Chi^2 = 5.30$, df = 2 (P = 0.07), $I^2 = 62.2\%$								



(c)

Study or Subgroup	Face mask Mean	SD	Total	No face mask Mean	SD	Total	Weight	Mean Difference IV, Random, 95% CI
1.10.1 Surgical mask								
Fikenzer et al. 2020 [3]	5.8	2.5	12	2.7	2.2	12	11.5%	3.10 [1.22, 4.98]
Kato et al. 2021 [40]	6.27	3.03	12	5.85	2.93	12	9.2%	0.42 [−1.96, 2.80]
Li et al. 2021 (Females) [41]	4.8	1.64	5	4.2	0.84	5	12.8%	0.60 [−1.02, 2.22]
Li et al. 2021 (Males) [41]	4.8	0.84	5	4.8	0.45	5	17.0%	0.00 [−0.84, 0.84]
Yoshihara et al. 2021 [47]	2.5	2.1	12	2.3	1.6	12	13.5%	0.20 [−1.29, 1.69]
Subtotal (95% CI)			**46**			**46**	**64.0%**	**0.73 [−0.29, 1.74]**
Heterogeneity: $Tau^2 = 0.70$; $Chi^2 = 8.85$, df = 4 (P = 0.06); $I^2 = 55\%$								
Test for overall effect: Z = 1.40 (P = 0.16)								
1.10.2 FFP2/N95								
Fikenzer et al. 2020 [3]	6.5	2.6	12	2.7	2.2	12	11.2%	3.80 [1.87, 5.73]
Kampert et al. 2021 [18]	7.5	3	20	4.8	3.7	20	10.5%	2.70 [0.61, 4.79]
Yoshihara et al. 2021 [47]	3.2	1.8	12	2.3	1.6	12	14.2%	0.90 [−0.46, 2.26]
Subtotal (95% CI)			**44**			**44**	**36.0%**	**2.35 [0.54, 4.17]**
Heterogeneity: $Tau^2 = 1.75$; $Chi^2 = 6.28$, df = 2 (P = 0.04); $I^2 = 68\%$								
Test for overall effect: Z = 2.54 (P = 0.01)								
Total (95% CI)			**90**			**90**	**100.0%**	**1.34 [0.34, 2.34]**
Heterogeneity: $Tau^2 = 1.34$; $Chi^2 = 22.38$, df = 7 (P = 0.002); $I^2 = 69\%$								
Test for overall effect: Z = 2.62 (P = 0.009)								
Test for subgroup differences: $Chi^2 = 2.35$, df = 1 (P = 0.13), $I^2 = 57.5\%$								

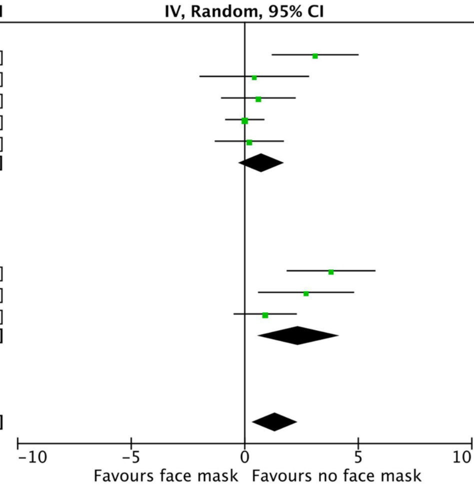


Fig. 5 (continued)

(d)

Study or Subgroup	Face mask Mean	SD	Total	No face mask Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.11.1 Surgical mask								
Fikenzer et al. 2020 [3]	4.2	2.4	12	2	1.3	12	13.5%	1.10 [0.23, 1.97]
Kato et al. 2021 [40]	9.2	2.16	12	8.11	1.76	12	14.3%	0.53 [−0.28, 1.35]
Roberge et al. 2012 [57]	6.31	0.79	20	6.2	0.85	20	17.9%	0.13 [−0.49, 0.75]
Yoshihara et al. 2021 [47]	6	0.7	12	5.8	0.4	12	14.5%	0.34 [−0.47, 1.15]
Subtotal (95% CI)			**56**			**56**	**60.2%**	**0.46 [0.06, 0.85]**
Heterogeneity: Tau² = 0.01; Chi² = 3.28, df = 3 (P = 0.35); I² = 8%								
Test for overall effect: Z = 2.24 (P = 0.02)								
1.11.2 FFP2/N95								
Fikenzer et al. 2020 [3]	6.2	2.3	12	2	1.3	12	11.0%	2.17 [1.13, 3.22]
Kim et al. 2016 [56]	6.6	0.5	12	6.4	0.5	12	14.5%	0.39 [−0.42, 1.20]
Yoshihara et al. 2021 [47]	6.1	0.7	12	5.8	0.4	12	14.3%	0.51 [−0.31, 1.32]
Subtotal (95% CI)			**36**			**36**	**39.8%**	**0.97 [−0.05, 2.00]**
Heterogeneity: Tau² = 0.62; Chi² = 8.08, df = 2 (P = 0.02); I² = 75%								
Test for overall effect: Z = 1.86 (P = 0.06)								
Total (95% CI)			**92**			**92**	**100.0%**	**0.67 [0.22, 1.12]**
Heterogeneity: Tau² = 0.19; Chi² = 12.89, df = 6 (P = 0.04); I² = 53%								
Test for overall effect: Z = 2.90 (P = 0.004)								
Test for subgroup differences: Chi² = 0.84, df = 1 (P = 0.36), I² = 0%								

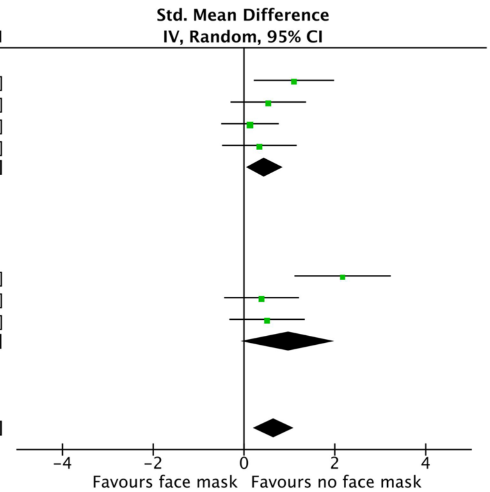


Fig. 5 (continued)

masks ($p=0.38$) or cloth masks ($p=0.07$). Furthermore, when only a progressive exercise test was included, a significant decrease was found in exercise performance ($p<0.01$), as shown in Table 2. For the sensitivity analyses, either a study with a high risk of bias [51] or a study that examined children [28] was removed, but the results remained consistent.

3.6 Risk of Bias and Publication Bias

RoB 2 and its additional considerations for crossover trials were employed to assess each publication's risk of bias. The details are presented in Table S2 (see ESM). In summary, six studies exhibited a low risk of bias [3, 25, 28, 29, 39, 62], 33 exhibited some concerns, and six exhibited a high risk of bias [37, 46, 51, 52, 57, 58]. Studies exhibited a high risk of bias mainly due to bias arising from period and carryover effects and missing outcome data. The publication biases of eight outcomes, namely exercise performance, heart rate, VO_2, saturation, $PetCO_2$, RPE, respiratory rate, and VE, are shown in Fig. S3 (see ESM).

4 Discussion

To our knowledge, this is the first systematic review and meta-analysis to examine the effects of wearing a mask during exercise on both physiological and psychological parameters in healthy individuals. The results of our systematic review revealed that wearing face masks during exercise negatively affected certain physiological outcomes (e.g., VO_2, $PetO_2$, SpO_2, VCO_2, and $PetCO_2$) and psychological variables (e.g., RPE, dyspnea, fatigue level, and thermal sensation), while a small effect was observed on exercise performance.

There was no significant change in heart rate when a mask was worn during exercise, which is consistent with the results of two previous systematic reviews [16, 17]. The sub-group analysis revealed no effect on heart rate during progressive exercise tests. As heart rate was measured at the end of exercise, the present review results suggest that wearing a face mask has a limited effect on maximum heart rate during exercise. Interestingly, when performing steady-state exercise, a significant increase in heart rate was observed; however, it should be noted that the increased value was limited to 2.7 bpm. Moreover, Shaw et al. reported a higher mean heart rate (2 bpm) in those who used FFP2/N95 respirators during exercise [16]. However, no effect was observed secondary to the use of any mask in the current review. This may be explained by the different population groups involved in the previous study. Specifically, the previous meta-analysis included heterogeneous populations (e.g., patients and healthy adults) [16], while only healthy populations were included in the current review.

The meta-analysis suggests that face masks worn during exercise significantly effect gas exchange, such as decreased VO_2, VCO_2, and $PetO_2$ and increased $PetCO_2$; these results are broadly consistent with those of previous reviews [16, 17]. According to the sub-group analysis, all abovementioned parameters showed similar changes between progressive exercise tests and steady-state exercise. Evidence from a previous study revealed that a reduction in VO_2 indicated a greater exercise efficiency [63]. However, this finding should be interpreted with caution, as only three trials were included in the analysis. A previous study reported decreased VO_2 when wearing a face mask during steady

Study or Subgroup	Face mask Mean	SD	Total	No face mask Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.1.1 Surgical mask								
Alkan et al. 2021 (18–25y) [50]	9.83	1.07	13	10.17	1.13	13	2.1%	−0.30 [−1.07, 0.47]
Alkan et al. 2021 (45–64y) [50]	6.88	1.92	13	8.05	1.88	13	2.1%	−0.60 [−1.38, 0.19]
Cabanillas-Barea et al. 2021 [25]	707.5	75.83	50	708.25	77.32	50	2.9%	−0.01 [−0.40, 0.38]
Dirol et al. 2021 [13]	530.7	67.85	100	545.2	71.23	100	3.1%	−0.21 [−0.49, 0.07]
Egger et al. 2021 [30]	4.8	0.4	16	5.1	0.5	16	2.3%	−0.65 [−1.36, 0.07]
Epstein et al. 2021 [14]	18.3	3.7	16	18.9	3.7	16	2.3%	−0.16 [−0.85, 0.54]
Fikenzer et al. 2020 [3]	3.3	0.5	12	3.4	0.5	12	2.1%	−0.19 [−1.00, 0.61]
Hua et al. 2021 [35]	12	0.85	23	14.4	0.78	23	2.0%	−2.89 [−3.74, −2.05]
Lässing et al. 2020 [42]	202.7	26	14	202.7	26	14	2.2%	0.00 [−0.74, 0.74]
Li et al. 2021 (Females) [41]	105.6	30	5	107.6	29.25	5	1.4%	−0.06 [−1.30, 1.18]
Li et al. 2021 (Males) [41]	184.8	26.81	5	187	28.15	5	1.4%	−0.07 [−1.31, 1.17]
Mapelli et al. 2021 [43]	187	52	12	194	57	12	2.1%	−0.12 [−0.92, 0.68]
Ng et al. 2022 [53]	269	56	8	278	56	8	1.8%	−0.15 [−1.13, 0.83]
Otsuka et al. 2020 [51]	108	37.9	6	104	30.6	6	1.5%	0.11 [−1.03, 1.24]
Pimenta et al. 2021 [60]	17.38	3.37	12	18.42	3.33	12	2.1%	−0.30 [−1.11, 0.51]
Rudi et al. 2021 [59]	219.5	71.9	20	230.5	77.3	20	2.5%	−0.14 [−0.77, 0.48]
Shaw et al. 2020 [45]	241	57	14	234	56	14	2.2%	0.12 [−0.62, 0.86]
Shaw et al. 2021 (Female) [28]	294	101	5	291	100	5	1.4%	0.03 [−1.21, 1.27]
Shaw et al. 2021 (Male) [28]	354	101	21	331	101	21	2.5%	0.22 [−0.38, 0.83]
Shui et al. 2022 [55]	136.71	40.07	12	143.51	39.63	12	2.1%	−0.16 [−0.97, 0.64]
Steinhilber et al. 2022 (130 W) [54]	1.84	0.72	39	1.91	0.7	39	2.8%	−0.10 [−0.54, 0.35]
Steinhilber et al. 2022 (150 W) [54]	2.32	0.81	39	2.35	0.83	39	2.8%	−0.04 [−0.48, 0.41]
Tornero-Aguilera et al. 2021 (400m) [34]	89.2	13.9	72	74.9	9.38	72	3.0%	1.20 [0.84, 1.56]
Tornero-Aguilera et al. 2021 (50m) [34]	9.62	1.76	72	8.55	0.84	72	3.0%	0.77 [0.43, 1.11]
Zhang et al. 2021 [48]	142.9	44.2	71	149.8	46	71	3.0%	−0.15 [−0.48, 0.18]
Subtotal (95% CI)			**670**			**670**	**56.7%**	**−0.12 [−0.39, 0.15]**
Heterogeneity: Tau² = 0.32; Chi² = 119.27, df = 24 (P < 0.00001); I² = 80%								
Test for overall effect: Z = 0.89 (P = 0.38)								
1.1.2 FFP2/N95								
Cabanillas-Barea et al. 2021 [25]	696.09	81.32	50	708.25	77.32	50	2.9%	−0.15 [−0.54, 0.24]
Egger et al. 2021 [30]	4.9	0.5	16	5.1	0.5	16	2.3%	−0.39 [−1.09, 0.31]
Epstein et al. 2021 [14]	18.5	3.6	16	18.9	3.7	16	2.3%	−0.11 [−0.80, 0.59]
Fikenzer et al. 2020 [3]	3.22	0.4	12	3.4	0.5	12	2.1%	−0.38 [−1.19, 0.43]
Hua et al. 2021 [35]	11.7	0.98	23	14.4	0.78	23	2.0%	−3.00 [−3.86, −2.13]
Kampert et al. 2021 [18]	545	141	20	591	145	20	2.5%	−0.32 [−0.94, 0.31]
Mapelli et al. 2021 [43]	184	54	12	194	57	12	2.1%	−0.17 [−0.98, 0.63]
Pimenta et al. 2021 [60]	17.35	3.38	12	18.42	3.33	12	2.1%	−0.31 [−1.11, 0.50]
Rudi et al. 2021 [59]	213.8	71.3	20	230.5	77.3	20	2.5%	−0.22 [−0.84, 0.40]
Shui et al. 2022 [55]	136.12	34.01	12	143.51	39.63	12	2.1%	−0.19 [−1.00, 0.61]
Steinhilber et al. 2022 (130 W) [54]	1.74	0.65	39	1.91	0.7	39	2.8%	−0.25 [−0.69, 0.20]
Steinhilber et al. 2022 (150 W) [54]	2.28	0.76	39	2.35	0.83	39	2.8%	−0.09 [−0.53, 0.36]
Subtotal (95% CI)			**271**			**271**	**28.4%**	**−0.42 [−0.76, −0.08]**
Heterogeneity: Tau² = 0.25; Chi² = 39.59, df = 11 (P < 0.0001); I² = 72%								
Test for overall effect: Z = 2.40 (P = 0.02)								
1.1.3 Cloth mask								
Dantas et al. 2021 [32]	4.28	0.27	10	4.5	0.26	10	1.9%	−0.79 [−1.71, 0.12]
Driver et al. 2021 [12]	10.97	2.27	31	12.63	2.28	31	2.7%	−0.72 [−1.24, −0.21]
Kampert et al. 2021 [18]	548	147	20	591	145	20	2.5%	−0.29 [−0.91, 0.33]
Shaw et al. 2020 [45]	241	51	14	234	56	14	2.2%	0.13 [−0.61, 0.87]
Steinhilber et al. 2022 (130 W) [54]	1.83	0.7	39	1.91	0.7	39	2.8%	−0.11 [−0.56, 0.33]
Steinhilber et al. 2022 (150 W) [54]	2.35	0.89	39	2.35	0.83	39	2.8%	0.00 [−0.44, 0.44]
Subtotal (95% CI)			**153**			**153**	**14.9%**	**−0.26 [−0.54, 0.02]**
Heterogeneity: Tau² = 0.04; Chi² = 7.15, df = 5 (P = 0.21); I² = 30%								
Test for overall effect: Z = 1.81 (P = 0.07)								
Total (95% CI)			**1094**			**1094**	**100.0%**	**−0.23 [−0.41, −0.04]**
Heterogeneity: Tau² = 0.28; Chi² = 180.09, df = 42 (P < 0.00001); I² = 77%								
Test for overall effect: Z = 2.36 (P = 0.02)								
Test for subgroup differences: Chi² = 1.84, df = 2 (P = 0.40), I² = 0%								

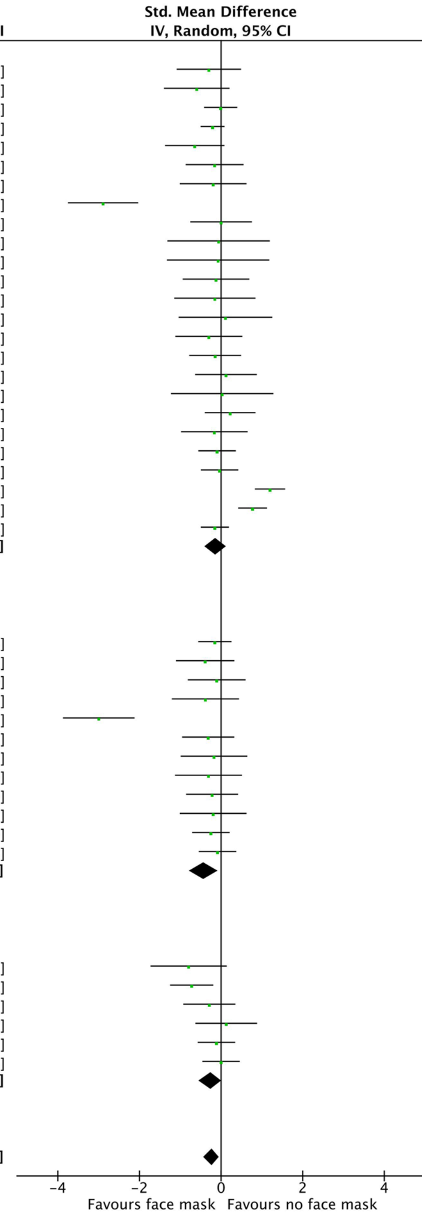


Fig. 6 Pooled analysis on the effect of face masks on exercise performance. Effects for the subgroups are based on the grouping variables of different types (surgical mask vs FFP2/N95 vs cloth mask). *FFP2* filtering facepiece 2, *N95* N95 respirator

exercise, and this change was explained by the reduction in alveolar ventilation induced by mask wearing, which leads to an increase in airway resistance [42]. Similarly, given the multiple layers and materials included in the construction of face masks, increased inspiratory resistance would likely decrease the amount of oxygen inhaled, resulting in a reduction in VO_2 and $PetO_2$ [14]. In addition to an increase in resistance, an increase in the dead space within the mask could lead to a decrease in VCO_2 and an increase in $PetCO_2$ [64]. Apart from the abovementioned factors, the dead space temperature and humidity were markedly elevated by the increased duration of mask use, with exercise leading to an additional increase in these factors and resulting in higher inspiratory resistance [48, 65].

Furthermore, a decrease in pulmonary function was also observed in the present review, including a reduction in VE, VT, and VE/VCO_2. As VT mediates the association between VE and VCO_2 [66], the results are in line with the effect of gas exchange. Such reduction is also likely to be caused by increased inspiratory resistance, especially during high-intensity exercise (e.g., the end of the progressive exercise test), as the decremental effects of inspiratory resistance are

associated with exercise intensity [67]. Consistently, for the sub-group analysis, the reduction in VE and VT was only observed in the progressive exercise test, while no difference was noted in steady-state exercise. Although these parameters revealed statistical differences between those wearing and not wearing face masks, the level of change was limited, and most values were still in the normal range, such as $PetCO_2$ within 35–45 mmHg and VE/VCO_2 between 20 and 30. However, the reduction in VE appeared to be relatively large (e.g., 14.46 L/min). This may be because the simultaneous wearing of the face mask can lead to gas leakage from the spirometry mask used to assess ventilation (i.e., insufficient seal to the face skin caused by wearing a face mask), especially for FFP2/N95 [68]. Future studies should therefore be aware of the potential biases in data collection when a spirometry apparatus is worn over a face mask for gas collection purposes, where greater restriction to breathing and interference with the expired gas measurement might have been imposed.

The present meta-analysis revealed a significant reduction in SpO_2 with the use of different face masks. The reduction in SpO_2 levels with the use of face masks could be owing to the higher $PetCO_2$ and the insufficient oxygen and carbon dioxide exchange due to CO_2 rebreathing (back into the lungs) [69]. Shaw et al. determined no change in SpO_2 with or without a face mask in 11 studies, while a significant reduction was observed only when maximal tests were included [16]. The reduction is comparable between our systematic review and Shaw et al.'s systematic review, i.e., 0.5 versus 0.6% [16]. It should be mentioned that the reduction of SpO_2 may be of minimal clinical relevance, as the values in most of the studies are still within the normal range of 95–100% [70]. Furthermore, no significant effect was observed on exercise performance in the present review in the sub-group analysis by either face mask type or by exercise type. Overall, our results on most physiological parameters are consistent with the previous systematic review and may further suggest that face masks pose only modest effects on physiological functions of the body system during exercise [16].

Four psychological variables were included in this review: RPE, dyspnea, fatigue level, and thermal sensation. RPE was the most commonly used indicator, and an increase in RPE was associated with using a surgical mask and in the total effect, which was consistent with the finding of a previous review [16]. Previous studies have shown that individuals wearing masks exhibit psychological discomfort, such as claustrophobia and dyspnea during exercise at high-intensity levels [12, 44]; this was consistent with the results obtained in our review. A significant increase was seen in the incidence of dyspnea among those wearing masks, which could partly explain the increase in RPE. Moreover, several studies have reported subjective discomfort associated with the use of masks during exercise, which was aggravated when the ambient temperature and humidity increased [3, 12, 44]. This subjective discomfort is mainly caused by dampening and deformation of the mask due to sweating during exercise, heat, tightness, and breathing resistance. The results of the meta-analysis also revealed that both fatigue levels and thermal sensation significantly increased when exercise was performed with a mask. Furthermore, increased inspiratory resistance and reduced pulmonary function may further exacerbate the subjective discomfort level. A previous study reported a significantly higher and clinically relevant incidence of dyspnea when wearing a surgical mask during exercise, while no effect was noted on distance using the 6-min walking test [71]. Further, compared with studies on physiological outcomes, limited studies have examined the effect of wearing a face mask on psychological variables; hence, more studies on this topic are warranted.

The current systematic review involved three types of face masks and a consistent pattern of findings was observed. For most outcomes, both surgical mask and FFP2/N95 respirators reached statistical significance, and the difference between FFP2/N95 respirators and no mask was generally larger than for surgical masks, such as PetCO2, 3.44 vs 2.32 mmHg. This could be explained by the difference in inspiratory resistance in the various face masks, i.e., two-fold higher for surgical masks compared with no mask (0.58 vs 0.32 kPa/L) [42], which is likely even higher for FFP2 masks [3]. Interestingly, our results revealed only a small difference in exercise performance for wearing face masks. Our data suggest that face masks could be worn during exercise with limited influence on performance. From a practical perspective, however, both surgical and cloth masks are widely recommended and used in daily life, whereas FFP2/N95 respirators are more commonly used in clinical settings [72]. Additionally, the WHO suggests that masks not be used during high-intensity exercise [73], which contrasts with the Centers for Disease Control's recommendations [74]. Only progressive exercise test was observed for significant effect when considering the exercise type, while limited studies examined the effects of steady-state exercise on exercise performance. Given the heavy spread of viruses in indoor exercise facilities, healthy individuals might consider wearing a face mask for protective purposes, even when high-intensity exercise is performed [74]. Nevertheless, healthcare professionals should cautiously evaluate each person's ability to exercise while wearing a mask and consider adjusting the prescription if appropriate (e.g., during exercise in a hot and humid environment).

The present systematic review included a comprehensive search strategy for both physiological and

psychological outcomes with three types of face masks (i.e., surgical mask, cloth mask, and FFP2/N95 respirators) that are commonly used by the public. In total, 45 studies were included in the systematic review, providing useful information for formulating appropriate health care policies and optimizing exercise recommendations for the public during the COVID-19 pandemic. Despite these strengths, the present review had certain limitations. First, only studies in English were included, hence some relevant studies in other languages might have been overlooked. Second, all the included studies assessing cardiopulmonary function used a sealed spirometry mask, which was placed over the face mask. Given this situation, the extra pressure exerted by the spirometry mask may further influence the breathing resistance and airflow, which may affect the gas exchange measurement, e.g., ventilation [44]. Moreover, it should be mentioned that all studies included in the current review were acute effect studies with healthy individuals. While most did not report adverse events during trials, suggesting that wearing face masks during exercise is safe in general, more interventional studies examining long-term effects and safety issues under different environmental conditions with various populations are needed.

5 Conclusion

This study provides a comprehensive explanation of the effects of exercising with different types of face masks on physiological and psychological factors. Wearing face masks during exercise generally showed modest effects on gas exchange, pulmonary function, and psychological outcomes in healthy individuals, while the effect on exercise performance appeared to be small. Further research on long-term face mask intervention is warranted.

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Declarations

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Code availability Not applicable.

Author contributions CZ, EP, and SW conceived and designed research; CZ, EP, DZ and KW performed review and meta-analysis; DZ and KW analyzed data; CZ and EP interpreted the results; CZ drafted manuscript; CZ, EP, and SW edited and revised the manuscript. All authors approved the final version of the manuscript.

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